AL/CF-TR-1995-0049

CARDIOPULMONARY RESPONSE TO PRESSURE BREATHING

Bryant W. Stolp
Stephen P. Arles
Guy de L. Dear
James M. Chimiak
Charles H. Gleaton
Lars L. Mielke
Richard E. Moon

F.G. Hall Environmental Laboratory
Hyper-Hypobaric Center
Duke University Medical Center
Durham, North Carolina 27710

CREW SYSTEMS DIRECTORATE
Crew Technology Division
2504 Gillingham Drive Suite 1
Brooks Air Force Base, Texas 78235-5104

May 1995

Final Technical Report for Period April 1993 - September 1994

ARMSTRONG LABORATORY

AIR FORCE MATERIEL COMMAND
BROOKS AIR FORCE BASE, TEXAS

NOTICES

This final report was submitted by the F.G. Hall Environmental Laboratory, Duke University Medical Center, Durham, North Carolina, under contract F33615-90-D0606, delivery order 0024, with the Armstrong Laboratory, Human Systems Center, AFMC, Brooks Air Force Base, Texas.

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely Government-related procurement, the United States Government incurs no responsibility or any obligation whatsoever. The fact that the Government may have formulated or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication, or otherwise in any manner construed, as licensing the holder of any other person or corporation; or as conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

The voluntary, fully informed consent of the subjects used in this research was obtained as required by AFR 169-3.

The Office of Public Affairs has reviewed this report, and it is releasable to the National Technical Information Service, where it will be available to the general public, including foreign nationals.

This report has been reviewed and is approved for publication.

Robert B. O'Connor

ROBERT B. O'CONNOR, Captain, USAF
Project Scientist

F. W. Y

F. WESLEY BAUMGARDNER, Ph.D.
Chief, Systems Research Branch

James P Dixon

JAMES P. DIXON, Colonel, USAF, BSC
Chief, Crew Technology Division

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	May 1995	Final April 93 - September 94

4. TITLE AND SUBTITLE
Cardiopulmonary Responses to Pressure Breathing

5. FUNDING NUMBERS
C - F33615-90-D-0606
PE - 63231F
PR - 2830
TA - 01
WU - 17

6. AUTHOR(S)
Bryant W. Stolp, Stephen P. Arles, Guy de L. Dear, James M. Chimiak, Charles H. Gleaton, Lars L. Mielke, Richard E. Moon

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
F.G. Hall Environmental Laboratory
Hyper-Hypobaric Center
Duke University Medical Center
Durham, N.C. 27710

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Armstrong Laboratory (AFMC)
Crews Systems Directorate
Crew Technology Division
2504 Gillingham Drive Suite 1
Brooks Air Force Base, TX 78235-5104

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
AL/CF-TR-1995-0049

11. SUPPLEMENTARY NOTES
Armstrong Laboratory Technical Monitor: Captain Robert B. O'Connor, (210)536-3545

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

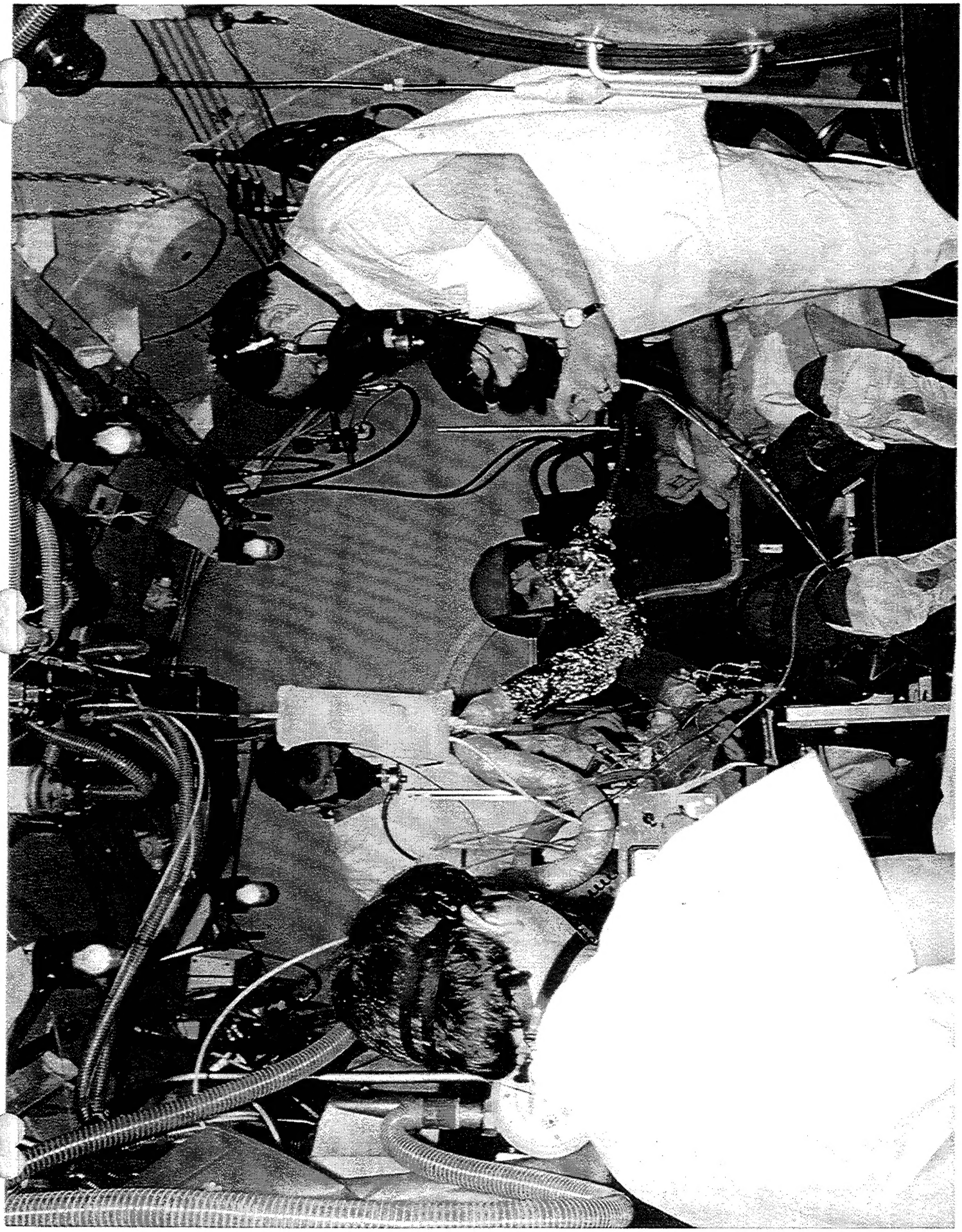
Investigators at the F.G. Hall Environmental Laboratory of the Duke University Medical Center studied the effects of positive pressure breathing (PPB) on pulmonary gas exchange. The multiple inert gas elimination techniques was used with 10 human subjects to quantify changes in ventilation/perfusion (V_a/Q) relationships during PPB. Subjects wore the Combined Advanced Technology Enhanced Design G Ensemble (COMBAT EDGE) with a 1:1 G-suit to mask pressure ratio. Experimental conditions included breathing air and 100% oxygen at 0, 30, and 60 mmHg of PPB at ground level and breathing 100% oxygen at 0 and 60 mmHg of PPB at 24,900 feet in an altitude chamber. Results showed the following: 1) an almost 5-fold increase in minute ventilation at 60 mmHg mask pressure; 2) PPB caused a shift of ventilation and perfusion to lung units at higher V_a/Qs; 3) the data supported the notion that PPB reduces shunt and perfusion to low V_a/Q lung units; 4) while oxygen breathing resulted in minor effects on some variables, there was a statistically significant effect of altitude exposure on heart rate, arterial blood pressure, and respiratory effects on hemodynamics; and 5) phasic swings in mask pressure seemed to augment venous return and sustain mean arterial pressures in some subjects during PPB.

14. SUBJECT TERMS
Ventilation/perfusion
Respiratory physiology
COMBAT EDGE
Positive pressure breathing
Multiple inert gas technique

15. NUMBER OF PAGES
86

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL



Frontispiece (previous page) shows an experiment in progress in the 'F' chamber, F.G. Hall Hypo-Hyperbaric Center at Duke University Medical Center. Subject TH is shown with BWS (back to the camera), LLM and REM. The subject is instrumented with EKG and catheters in the radial artery, pulmonary artery and subclavian vein. In order to prevent condensation in the expired limb of the breathing circuit or the mixing box these components were maintained above 45°C by a hydraulic heating system. Foil is wrapped around the breathing circuit to provide additional insulation.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

Positive pressure breathing (PPB) is used to maintain the alveolar partial pressure of oxygen during altitude exposures in excess of 12,000 meters (36,000 feet). At altitudes up to 33,000 feet the alveolar gas tensions may be kept within the normal range by increasing the concentration of oxygen in the inspired gas mixture. Above this altitude, however, alveolar oxygen tensions fall below normal levels despite breathing 100% oxygen (Sharp & Ernsting, 1988). Furthermore, during high-acceleration (high-G) maneuvers, even at lower altitudes, there is a tendency for microatelectasis formation and development of intrapulmonary right-to-left shunt, which may be accentuated during 100% oxygen breathing (Wagner, et al. 1977). Raising the pressure inside the breathing circuit throughout the breathing cycle (PPB) is well established as a method of maintaining alveolar oxygen tension at high altitudes (Gagge, et al. 1945) and under high G-forces. Burns and Balldin (1988) studied the rates of arterial desaturation during acceleration with positive pressure breathing at 50 mmHg and 70 mmHg. They found that the rate of oxygen desaturation was less with PPB than without PPB suggesting a possible improvement in $\dot{V}_A/\dot{Q}$ relationships, at least in low $\dot{V}_A/\dot{Q}$ regions or shunt. This is equivalent to continuous positive airway pressure (CPAP) used clinically to augment arterial oxygenation in patients.

PPB may have detrimental effects, however. Increased airway pressures can cause pharyngeal discomfort with throat and neck distention, as well as creating difficulties in the maintenance of a tight mask seal. The increased intrapulmonary pressure can result in lung hyperexpansion. This is minimized by the use of a counterpressure vest (Burns and Balldin, 1988). The increase in intrathoracic pressure also results in diminished cardiac output due to decreased venous return from peripheral capacitance vessels and may eventually induce syncopal symptoms (Goodman et al, 1992; Ackles et al, 1978; Balldin & Wranne, 1980). In patients treated with CPAP, reduced cardiac output and renal blood flow have also been observed. PPB at 30 mmHg without chest counterpressure and at 60 mmHg with counterpressure causes increased tidal volume, minute ventilation, oxygen consumption and carbon dioxide elimination (Ernsting, 1977). While nitrogen clearance curves indicate that the distribution of inspired gas in the lung is minimally changed with PPB, Fenn et al (1947) estimated that nearly 50% of the blood in the lung is displaced during PPB at slightly over 20 mmHg. It is therefore likely that PPB causes an increase in high ventilation perfusion ($\dot{V}_A/\dot{Q}$) areas in the lung, and hence impairment of carbon dioxide exchange, providing an explanation for the hyperpnea (and hence increased work of breathing) that usually results.

The purpose of this study was to investigate the cause of the well described hyperventilation associated with moderate to high levels of PPB. It was hypothesized that PPB with both chest counterpressure and leg compression from an anti-G suit reduces perfusion to low $\dot{V}_A/\dot{Q}$ units in the lung while increasing the ventilation of high $\dot{V}_A/\dot{Q}$ units. It was also hypothesized that microatelectasis induced by 100% oxygen breathing (Wagner et al, 1974) would be reduced by PPB. The multiple inert gas elimination (MIG) technique was used to quantify the changes in $\dot{V}_A/\dot{Q}$ relationships during PPB using the COMBAT EDGE that uses positive pressure breathing, a chest counterpressure vest and an anti-G suit.

METHODS

Selection of Subjects

Ten healthy male volunteers were selected for the study. Anthropometric data are summarized in Table 1. Age ranged from 20 to 33 years (mean 27). All lived near Durham, North Carolina

Table 1. Anthropometric and Pulmonary Function Data

Subject	Sex	Age yr	Height cm	Weight kg	Hb g/dl	FVC liters %pred	FEV1 liters %pred	FEF25-75 l/s %pred	TLC liters %pred	MVV l/m %pred	DLCO ml/min/mmHg %pred
RT	M	33	185	89	13.9	5.87	3.87	2.55	7.69	147	33.70
						102	*83*	*55*	*102*	*94*	*104*
KK	M	27	185	86	11.0	6.35	5.59	6.20	7.53	160	44.00
						108	*116*	*127*	*100*	*99*	*132*
FC	M	33	188	102	13.2	6.44	4.90	4.08	8.34	208	33.00
						109	*102*	*87*	*108*	*130*	*101*
VW	M	21	188	90	13.1	5.85	4.97	5.60	7.20	176	43.60
						95	*98*	*108*	*94*	*104*	*126*
WS	M	28	173	67	11.8	5.11	4.27	4.43	6.30	128	37.60
						100	*100*	*96*	*97*	*88*	*118*
TH	M	30	183	75	13.6	5.34	4.43	4.84	7.74	199	34.30
						94	*95*	*102*	*106*	*128*	*105*
JL	M	26	168	84	12.5	5.28	4.03	3.47	6.88	133	30.40
						109	*98*	*76*	*113*	*94*	*96*
TLH	M	21	177	79	13.4	5.75	3.96	2.80	7.07	143	38.30
						103	*85*	*56*	*103*	*91*	*114*
SA	M	28	178	98	12.0	6.18	4.86	4.51	7.39	176	33.80
						114	*108*	*96*	*107*	*116*	*104*
TP	M	20	168	61	13.5	4.09	3.63	5.00	5.11	150	27.80
						82	*85*	*104*	*84*	*103*	*85*
Means		27	179	83	12.8	5.62	4.45	4.35	7.13	162	35.7
SD		4.8	7.7	12.9	0.9	0.70	0.61	1.16	0.90	27	5.3
% Predicted Means						*102*	*97*	*91*	*101*	*105*	*109*
SD						*9*	*11*	*23*	*8*	*15*	*14*

FVC, forced vital capacity; FEV1, forced expired volume in 1 second; FEF25-75, mean flow rate over middle 50 % of forced expiration; TLC, total lung capacity; MVV maximum voluntary ventilation; DLCO, carbon monoxide diffusing capacity.
Percent of predicted values shown under each variable.

(elevation 460 ft). Subjects were screened for gross obesity and history of cardio-pulmonary disease. All subjects were non-smokers, although one had smoked previously for a short time. Spirometry, lung volumes and carbon monoxide transfer factor were measured on each subject and all were within normal limits. Total lung capacity was determined by body plethysmography. Two subjects had FEF_{25-75}, which were 55% of predicted for age and height, and one had a FEF_{25-75}, 76% of predicted value. All subjects had normal posterior-anterior and lateral chest radiographs, normal 12 lead EKGs and normal resting arterial blood gases. Each subject was briefed on the risks of pulmonary artery catheterization. Subjects unfamiliar with pulmonary artery catheterization watched a videotape demonstrating the procedure. The risks of positive pressure breathing and altitude were also explained and informed consent was obtained in accordance with the guidelines of the Duke University Institutional Review Board for Human Experimentation (Protocol #1204-93-9: consent form appended).

Training

Prior to the experiment, each subject underwent a series of 1-3 training sessions in order to become familiar with the equipment and to become accustomed to positive pressure breathing. Subjects became eligible for the study after demonstrating that they could maintain steady-state breathing patterns at both 30 and 60 mmHg mask pressure for a minimum of five minutes. As a safety measure, subjects were instructed on how to break the mask pressure seal by jaw movement in case they felt overwhelmed by the pressure. One subject (VW) had previous experience with positive pressure breathing and because of time commitments was unable to attend a training session prior to his actual study.

Experimental Set Up

All studies were performed in "F" chamber at the F.G. Hall Environmental Laboratory at Duke University Medical Center. A color photograph of the experimental set-up is included at the beginning of this report and is labeled in Fig. 1. The subject was seated in a semi-reclined position to simulate the position of the pilot in an F-16 during flight. The CRU-93 pressure demand regulator supplied gas to the breathing mask, the chest counterpressure vest and anti-G suit (see below). Expired gas was conducted through a heated expiratory tube and mixing box into a Douglas bag. Expired bag volume was measured with a calibrated gasometer. The bag was emptied to a standard pressure of negative 5 cm of water that was adjusted through a pop-off valve on the gasometer. The subject was instrumented with pulmonary artery and peripheral arterial catheters (see text). A dilute solution of inert gases was infused by a central venous catheter inserted via the contralateral basilic vein. Electrical signals were conducted via through-hull penetrators to a cardiac monitor and to a standard patient monitor (see below). The analog outputs from these monitors were connected to an 8 channel A/D converter outside the chamber and then to a digital computer for data storage and analysis. Chamber pressure was monitored with a model 370 digital pressure gauge (Setra Systems, Acton, MA) and a model 65C-1G-2002X differential pressure gauge (Wallace & Tiernan, Belleville, NJ).

Breathing Circuit. The COMBAT EDGE manside test kit was installed in the hypobaric chamber and connected to a high-volume regulator set between 80 and 100 psig. Breathing gas was delivered to the oronasal mask from the CRU-93 pressure demand regulator via a chest-mounted manifold (CRU-94/P Integrated Terminal Block or ITB). During PPB, gas was also delivered from the regulator to the chest counterpressure vest via the ITB. In addition, regulated gas was supplied to bladders located in the flight helmet as an assist in maintaining a tight mask seal. The

A/D Converter
Flow Meters
PPB Controller
Gas Supply
Thermodilution
Cardiac Output
Apparatus
Transducers
Peripheral IV
Mix Solution
Pump
To
Mixing Box
Vacuum
Pop-Off
Valve

Figure 1

CSU-13B/P anti-G suit was inflated in a conventional manner via a direct line from the control panel of the COMBAT EDGE manside test kit. Breathing gas pressures of 0 mmHg, 30 mmHg, or 60 mmHg were provided according to the experimental protocol (see below). Pressure was either provided to the mask alone or in a 1:1 pressure ratio to the mask, the upper-body counter-pressure garment, the helmet bladder, and the G-suit as outlined.

The first two studies (RT, KK) were performed using the Type A-14 pressure-demand regulator (Firewel, Buffalo, NY), supplied with the COMBAT EDGE manside test kit. During subsequent subject training periods, it was found that for some subjects this regulator generated undesirable mask pressure fluctuations (10-20 mmHg) at 60 mmHg in response to some patterns of breathing. Therefore, a Type CRU-93A Pressure-Demand Regulator (Litton Instruments) was obtained and used for all subsequent studies. This regulator was able to maintain the desired mask (PPB) pressures within a narrower range during sustained breathing tests for most subjects. Breathing gas supplied to the oronasal mask was plumbed through a model 3800 pneumotach (Hans Rudolph, Kansas City, MO) and a model 5410 volume monitor (Ohmeda, Englewood, CO) in order to monitor inspired gas volumes and breathing frequencies. While the take-off for gas supplied to the chest counterpressure vest and helmet bladders was upstream of these flowmeters, for ease of presentation they are depicted in Figure 1 as being downstream. Volume calibration was achieved prior to each experiment using a standard 3 liter calibration syringe (Warren E. Collins, Braintree, MA). Exhaled gas was conducted through standard 38 mm ID corrugated respiratory tubing into a 9-liter mixing box. The tubing and mixing box were both heated to greater than 45°C in order to prevent condensation of exhaled water vapor and subsequent trapping of water soluble inert gases (especially ether and acetone) (see below). The exhaled gas was collected into a 60 liter Douglas bag (Warren E. Collins, Braintree, MA) for subsequent volume determination and metabolic gas sampling. Douglas bag volume was measured using a calibrated model DTM-325 dry gasometer (American Meter Company, Nebraska City, NE). Appropriate temperatures and barometric pressures were recorded for later use in conversion of gas volumes to either STPD (metabolic studies) or BTPS (ventilatory measurements).

Cardiovascular Monitoring. Model T12AD-R disposable pressure transducers (Viggo-Spectramed, Oxnard, CA) for the mask (Pm), central venous (CVP), pulmonary artery (Ppa) and arterial pressures (Part) were placed inside the chamber and connected via through-hull penetrators to Space Lab model 512 and model 514 patient monitors (Space Labs, Hillsboro, OR). A 5-lead ECG was similarly connected to the Space Labs model 512. A model 9520A cold injectate delivery system (American Edwards Laboratories, Anasco, PR) was wired to a Horizon 2000 monitor (Mennen Medical, Clarence, NY) to obtain thermodilution cardiac output measurements. Pressure transducers were calibrated with an anaeroid gauge prior to each experimental run.

Data Acquisition and Storage. All signals were digitized to a Macintosh IIfx personal computer (Apple Computers, Cupertino, CA) at 200 Hz using a MacLab MK III eight-channel data acquisition system (Analog Digital Instruments, Milford, MA). Data were transferred to an Excel spreadsheet (Microsoft, Redmond, WA) for subsequent statistical analysis (see page 11).

Subject Instrumentation

On the morning of the study the flight helmet, face mask, chest counterpressure vest and anti-G suit were fitted to the subject prior to any medical intervention. The subject's skin was prepared

for ECG electrode placement with Omni prep (DO Weaver and Company, Aurora, CO). Silvon Diaphoretic ECG electrodes (NDM, Dayton, OH) were applied. Prior to insertion of the arterial catheter, adequacy of ulnar collateral circulation was established in all subjects using the Allen Test. Using local anesthesia, a 20 gauge, 2 inch arterial catheter was placed in the radial artery of the non-dominant wrist.

Originally it was planned to infuse multiple inert gas (MIG) solution (see below) via a peripheral venous catheter. However, the large changes in peripheral venous pressure that occur during positive pressure breathing (PPB) appeared to have a substantial effect on limb blood flow. Preliminary experiments demonstrated that the delivery of MIG solution to the central circulation was significantly reduced under conditions of high PPB. Peripheral venous infusion of inert gas solution would therefore result in non-uniform delivery to the lung, a fundamental requirement of the technique. Therefore, 18 or 15 gauge central venous catheters (Sorenson Research, Salt Lake City, UT) were placed in all subjects for the purpose of MIG solution infusion. These were inserted via the basilic vein and advanced under radiographic guidance into the ipsilateral subclavian vein. In the other arm an 8.5 French rapid infusion introducer with a side port hemostasis valve (Arrow, Redding, PA) was inserted into the basilic vein. A #7 French Edwards Swan-Ganz TD pulmonary artery catheter (Baxter, Irvine, CA) was inserted into the main pulmonary artery under radiographic imaging and continuous EKG and pressure monitoring. This catheter has central venous and pulmonary artery pressure/sampling ports, a balloon tip for pulmonary capillary wedge pressure determination and thermistors for thermodilution cardiac output determination.

Inert Gas Measurements

Preparation of Infusate. The MIG infusate was prepared in a sterile fashion prior to each study as follows. Residual air was extracted from each of two 1-liter bags of lactated Ringer's solution. A 100 ml mixture of gas consisting of 1.2% sulfur hexafluoride, 15% clyclopropane, balance ethane was added to the bag through a sterile Millex-FG 0.2μ filter (Millipore, Bedford, MA). The bag was shaken vigorously for ten minutes. The gas was withdrawn and the procedure repeated. After removing all residual bubbles, 10 ml of acetone, 1.5 ml of diethyl ether and 5 ml of enflurane were added to the bag. The solution was then infused through a 0.22 micron high-pressure filter (IVEX-HP Filterset, Abbott, North Chicago, IL) and into the subject via the central venous Sorenson catheter. The infusion was delivered at 5 ml per minute using a model 7553-80 roller pump (Cole-Parmer, Chicago, IL). Calibration of the infusion pump was performed daily using a graduated cylinder and stopwatch.

Blood and Gas Sample Collection. On each day solubilities of each of the six inert gases were measured by double extraction on samples of the subject's blood. Blood samples for each experimental condition were collected in 10 ml heparinized matched glass syringes (Eisele and Company, Nashville, TN or Becton-Dickinson, Rutherford, NJ). Inert gas blood samples were tonometered with an approximately equal volume of ultra high purity nitrogen, which was then expressed into a transfer syringe and the gas analyzed with a Varian model 3700 gas chromatograph (Varian, Sunnyvale, CA). Expired inert gas samples were collected in 100 ml ungreased, matched glass syringes (Becton-Dickinson, Rutherford, NJ) and injected directly into the gas chromatograph. The injected sample was conducted to both the flame ionization detector (ethane, cyclopropane, ether, acetone, enflurane) via a Porapak T 80/100 mesh column (Varian, Sunnyvale, CA) and the electron capture device (sulfur hexafluoride) via a molecular sieve 5A 45/60 mesh column(Varian, Sunnyvale, CA).

Data Acquisition and Storage. Analog output signals were digitized using a Nelson analytical 900 series interface (Nelson Analytical, Cupertino, CA). The data were stored on a Gateway 2000 486/33 personal computer for subsequent analysis.

Cardiopulmonary Measurements

Throughout the day the subject's condition was monitored continuously by a physician at the altitude chamber for fatigue, mental status changes, electrocardiographic changes and blood pressures. Digitized data were collected during the ten minutes before and after each study. These were later analyzed for heart rate, systolic and diastolic arterial blood pressure, mean arterial, pulmonary artery, central venous and mask pressures, maximum and minimum mask pressures, and respiratory rate. Pulmonary capillary wedge pressure (PCWP) and central venous pressure (CVP) were also recorded at end expiration for later analysis. These values were taken over at least three consecutive respiratory cycles in order to assure reproducible measurements. Wedge pressures and CVP pressures measured at end expiration were discarded if the subject experienced a mask leak during measurement and was unable to maintain a constant mouthpiece pressure. Heart rates were averaged over a 10-20 second period during each minute of the experiment. Corresponding blood pressure measurements were obtained over the same time period if the pressure catheters were not being flushed and were not being used for blood sampling. When this was the case, the next 10-20 second period was measured and average values recorded for that minute's representative data. On rare occasions the blood pressure measurements could not be obtained for a given minute due to clotting in the catheter, necessitating thorough repeated flushing. This problem was ameliorated during the latter 6 studies by the addition of heparin to the flush solution in a concentration of 1 unit/ml. An additional problem encountered during most altitude experiments was damping of the pressure waveforms due to formation of bubbles in the catheters and flush solution. Careful attention to eliminating bubbles prior to data collection improved the signals in these cases. Additionally, the flush solutions for the arterial catheter and the Swan-Ganz catheter were degassed prior to ascent to altitude. This seemed to improve, although not entirely eliminate, bubble formation at 24,900 feet.

Cardiac output. Fick cardiac outputs were determined during each experiment using 3 of the 6 inert gases and oxygen. Thermodilution cardiac outputs were also obtained in the last 8 subjects. Thermodilution curves were repeated until either the subject became fatigued, was unable to maintain a good mask seal, or until two consecutive cardiac outputs were reproducible.

Minute ventilation. Minute ventilation values are reported as BTPS using ambient chamber barometric pressure. During runs at increased mask pressure, when intrathoracic pressure exceeds ambient pressure, the usual calculations of BTPS ventilations therefore slightly overestimate the volume of gas moved through the breathing circuit. This does not affect blood gas measurements, or calculations of oxygen and carbon dioxide exchange. The effect on dead space is discussed below.

Oxygen consumption and carbon dioxide elimination. Mixed expired samples were withdrawn from the Douglas bags in 100 ml glass syringes pre-wetted with lactic acid. Expired oxygen and carbon dioxide concentrations were determined by gas chromatography with model S-1 chromatographs (Quintron, Milwaukee, WI). A 13X molecular sieve 80/100 mesh column was used for oxygen analysis and a Porapak Q 80/100 mesh column was used for carbon dioxide analysis.

Metabolic Calculations: $\dot{V}O_2$ (oxygen consumption), $\dot{V}CO_2$ (carbon dioxide elimination rate) and R (respiratory quotient) during air breathing experiments were calculated according to the following equations. Oxygen consumption was not determined while breathing 100% oxygen since the equations are invalid under these conditions. Carbon dioxide elimination rate was calculated during 100% oxygen breathing experiments by multiplying the mixed expired fraction of carbon dioxide by the expired gas volume (inspired fraction of carbon dioxide equals 0.0).

$$\dot{V}O_2 = \left(F_IO_2 \frac{F_EN_2}{F_IN_2} - F_EO_2 \right) \dot{V}_E$$

$$\dot{V}CO_2 = \left(F_ECO_2 - \frac{F_EN_2}{F_IN_2} F_ICO_2 \right) \dot{V}_E$$

$$R = \frac{\dot{V}CO_2}{\dot{V}O_2}$$

where: F represents the fractional concentration of each component gas in samples of dried inspired (I) and mixed expired (E) samples.

Dead space was calculated using the Enghoff modification of the Bohr equation:

$$V_D / V_T = \left[1 - \frac{P_ECO_2}{P_aCO_2} \right]$$

P_ECO_2 is conventionally derived from the ambient pressure and the fractional concentration of carbon dioxide in each mixed expired gas sample. However, when mask pressure is elevated the entire breathing circuit and tracheobronchial tree are at increased ambient pressure (Pbar + 30 or Pbar + 60 mmHg). Compared to values calculated using ambient (chamber) pressure, dead space calculated using mask pressure is therefore somewhat lower. When mask pressure is 60 mmHg, the downward adjustment of dead space at ground level is around 16% and 30% at 24,900 feet altitude. Thus, adjusted values for dead space were also calculated (see Summary of Blood Gases and Ventilation in Appendix). All reported blood gas tensions reflect the tensions within a liquid and therefore do not require an adjustment for mask pressure.

Statistics

In order to test the effect of experimental conditions, a 3-factor ANOVA was used. Statistical significance was defined as $P < 0.05$. When statistically significant effects were observed, post-hoc paired comparisons were made using the Tukey-Kramer test.

Safety Considerations

All subjects were healthy volunteers and safety was a prime concern. To minimize potential complications of pulmonary artery catheterization, advancement of the catheter was visualized directly under fluoroscopy in addition to continuously monitoring the pressure wave form and ECG.

Once in the chamber, the subject was continuously monitored for ECG, pulmonary artery, central venous and arterial blood pressures throughout the day. At least three of the four experimenters in the chamber were physicians. Another physician was outside the chamber monitoring both physiological signals and a closed circuit video signal of the chamber personnel. The chamber operator was also monitoring the closed-circuit video system. Additionally, the four inside experimenters were in constant communication with the chamber operator, monitoring physician and each other via two way headsets.

Experimental Protocol

The matrix of experimental conditions is shown in Table 2 below.

Table 2:

Altitude (feet)	FiO_2	Mask Pressure (mmHg)	G-suit Pressure (mmHg)	Thoracic Counterpressure (mmHg)
460	0.21	0	0	0
460	0.21	30	30	30
460	0.21	30	0	0
460	0.21	60	60	60
460	1.0	0	0	0
460	1.0	60	60	60
24,900	1.0	0	0	0
24,900	1.0	60	60	60

The six ground-level runs were conducted at ambient barometric pressure (P_B) with the chamber door open (mean P_B = 756 mmHg, range 741-764 mmHg). For altitude measurements, the chamber was decompressed at a rate of 2500 ft/min to a simulated altitude of 24,900 feet (P_B = 282 mmHg). This altitude was chosen as a compromise between minimizing oxygen prebreathing requirements needed to decrease decompression sickness risk for inside personnel and an attempt to maximize simulation of high-altitude gas density and hypoxia. Prior to going to altitude, all chamber occupants breathed 100% oxygen for at least 30 minutes in order to minimize the possibility of decompression illness. They remained on oxygen throughout the altitude exposure and during the return to the ground level. The descent rate was similar to the ascent rate with stops made when necessary if significant middle-ear discomfort was noted by the inside personnel. After each change in altitude, the chamber temperature was allowed to stabilize before beginning the pressure and volume calibrations prior to the next run.

In order to attain sufficient blood levels of the inert gases, the MIG infusion was delivered for at least 45 minutes prior to beginning the first study. Infusion was maintained throughout the day until the end of the last randomized study. Each experimental period lasted 3.5 - 12 minutes. Table 3 shows the minute-by-minute protocol which is summarized as follows. The target pressure was delivered following pressure and volume calibration and verification of adequate electrical signals on the data acquisition system. The experimental clock was started following attainment of steady-state minute ventilation, breathing pattern, heart rate and blood pressure. Minute ventilation was monitored on-line from the Ohmeda 5410 volume monitor in the chamber while the remainder of physiological parameters were monitored by the medical officer outside the chamber. The Douglas bag was opened and duplicate arterial and mixed venous inert gas blood samples were obtained after two minutes of steady-state breathing. The corresponding inert gas mixed expired sample was collected from the mixing box after real-time calculation of the transit time between the mouth and expired gas sampling port. Inert gas (MIG) blood samples were generally obtained by constant aspiration over the course of one minute. However, during 60 mm mask pressure runs, which were often limited by subject tolerance, 30 second samples were usually obtained. Separate arterial and venous blood samples were drawn for analysis of hemoglobin (Hb), hematocrit (Hct), partial pressure of arterial and mixed venous oxygen and carbon dioxide (PaO_2, $PaCO_2$, $P\bar{v}O_2$, $P\bar{v}CO_2$), arterial and mixed venous pH (pHa, $pH\bar{v}$), and arterial and mixed venous oxygen saturation (SaO_2, $S\bar{v}O_2$). The blood volume collected for each run was approximately 30 ml; the total volume was less than 300 ml/day.

After all blood samples had been drawn and the lines flushed, 2-4 thermodilution cardiac outputswere obtained. Pulmonary artery wedge pressure measurements were obtained by inflating the balloon on the pulmonary artery catheter until the wedge wave form was verified by the outside medical officer. The balloon remained inflated over several respiratory cycles to provide reproducible end-expiratory measurements. Each experimental period was stopped after all samples and measurements had been obtained, when the subject indicated that he could not continue any longer, or when pre-syncopal symptoms were noted.

The order of experimental conditions was randomized within certain constraints. The second subject (KK) developed severe abdominal distress at altitude after performing a 60 mmHg run at ground level. Subsequent altitude studies always preceded ground-level pressure runs of 60 mmHg in order to minimize the intake of gastrointestinal gas at ground level that, because of expansion, could then induce discomfort during ascent.

Table 3: Protocol Schedule

Time	Event	Comments
-5:00 to -2:00	Calibration.	
-2:00 to 0:00	Baseline data acquisition at rest.	
0:00	Start target PPB	
0:00 to 2:00	Verify steady-state HR, BP, and V_E.	Calculate tau.
2:00	Open expired gas collection bag.	Record P_B, Tchamber and Tbox.
2:30	Start MIG blood draw.	
3:30	Stop MIG blood draw.*	
3:45	Start arterial and mixed venous blood gas draw.	
4:00 (approximately)	Collect MIG expired gas sample from mixing chamber.**	Sample time dependent on tau.
4:15	Stop arterial and mixed venous blood gas draw.	
4:30	Start replicate MIG blood draw.	
5:00	Close expired gas collection bag.	
5:30	Stop replicate MIG blood draw.*	
6:00 (approximately)	Collect replicate MIG expired gas sample.**	Sample time dependent on tau.
6:00 to 7:00	Obtain duplicate thermodilution cardiac outputs. Obtain duplicate IC, FVC (insp).	
7:00	Stop PPB	
6:30 to 9:00	Sample expired gas collection bag for F_EO2 and F_ECO2.	
	Measure expired gas collection bag volume.	Record P_B, Tchamber, Tbox and Tspirometer.
8:00 to 10:00	Stop data acquisition when HR, BP and V_E are back to baseline.	

* MIG blood sample time reduced to 30 seconds for 60 mmHg runs. Target time for PPB reduced to 6 minutes.

** MIG expired gas sample time determine by tau (transit time through the mixing box).

Subject tolerance did not always allow replicate samples. This combined with 30 second sampling reduced target PPB time to 5 minutes.

Data Analysis

Inert Gas Calculations: Under each experimental condition, for each inert gas, retention ($Pa/P\bar{v}$) and excretion ($P_E/P\bar{v}$) were calculated. With a FORTRAN program on a Gateway personal computer, using the method of ridge regression (Wagner et al, 1974), a 50-compartment distribution of ventilation and perfusion was obtained. Shunt ($\dot{Q}_S/\dot{Q}_t$: $\dot{V}_A/\dot{Q} = 0$) and dead space (V_D/V_T: $\dot{V}_A/\dot{Q} = \infty$) represent the extremes of this distribution. Log standard deviations of the ventilation and perfusion distributions ($\log SD_{\dot{V}}$, $\log SD_{\dot{Q}}$) provide indices of ventilation-perfusion mismatching (Evans & Wagner, 1977). Additional parameters obtained directly from the inert gas measurements, without requiring the 50-compartment distribution, were calculated as follows (Gale et al, 1985):

$$DISP_{R\text{-}E} = 100 \times \sqrt{\frac{\sum_{i=1}^{n} (R_i - E_i^*)^2}{n}}$$

$$DISP_R = 100 \times \sqrt{\frac{\sum_{i=1}^{n} (R_i - RH_i)^2}{n}}$$

$$DISP_E = 100 \times \sqrt{\frac{\sum_{i=1}^{n} (EH_i - E_i^*)^2}{n}}$$

where

$$EH_i = RH_i = \frac{\lambda_i}{\lambda_i + \dot{V}_A/\dot{Q}_T}$$

and

$$\dot{V}_A = \dot{V}_E(1 - V_D / V_T)$$

$\dot{Q}_T$ is the cardiac output. λ_i are the blood:gas partition coefficients of the six inert gases. E^*i are the excretions corrected for dead space: $E^*i = \frac{Ei/}{(1-V_D/V_T)}$, where V_D/V_T is obtained from the maximum possible dead space ventilation calculated directly from inert gas retention measurements (Gale et al, 1985). $DISP_E$ and $DISP_R$ are, respectively, the root mean square differences between the measured excretions and retentions of the six inert gases, and those of a homogeneous lung with the same cardiac output and alveolar ventilation as the one being studied. $DISP_{R\text{-}E}$ is the root mean square differences between measured retention and excretions.

RESULTS

Complications

Subjects had no complications from the invasive monitoring. No subject experienced clinical signs of pulmonary injury as a result of positive pressure breathing.

One subject (KK) experienced abdominal gaseous distension, causing severe cramping, after ascent to altitude. The altitude portion of the study was aborted, and the symptoms were promptly relieved after returning the chamber to ground-level pressure. It was hypothesized that gastric insufflation from a prior high mask pressure run had precipitated the problem. Thereafter all subjects completed the altitude portion of the study prior to performance of any ground-level experiment requiring high mask pressure (60 mmHg). No complications occurred when altitude experiments followed any of the 30 mmHg pressure experiments at ground level.

Two subjects (TLH, TP) developed wrist discomfort after ascent to altitude, both on the side of the arterial catheter. In one subject (TP) the discomfort was of such severity that the chamber was recompressed after completing only one of two runs at altitude. Symptoms in both subjects resolved promptly during recompression of the chamber with no sequelae. The cause of these symptoms was believed to be decompression illness. No further treatment was required.

One subject (VW) developed ear squeeze and another subject (TP) experienced tooth squeeze during descent from altitude. Recompression was performed at a reduced rate, and neither subject experienced sequelae.

General Results

The following graphs summarize the experimental results. Minute-by-minute data were acquired as described under the section "Cardiopulmonary Measurements". Graphs of mean data comparing the various conditions represent steady-state values obtained during the last minutes of each run.

Fig. 2 depicts mean mask pressure vs time for all conditions while breathing air. Mean mask pressure was maintained within 4 mmHg of target pressure during all experimental runs. The magnitude of mask pressure swings during the 60 mmHg experimental runs depended on breathing pattern. Pressures occasionally ranged from 45 mmHg to 69 mmHg in some subjects who had breathing patterns using very short inspiratory times. This was improved but not entirely eliminated after replacement of the A-14 regulator with the newer CRU-93A. Mean mask pressures were similar during O_2 breathing runs.

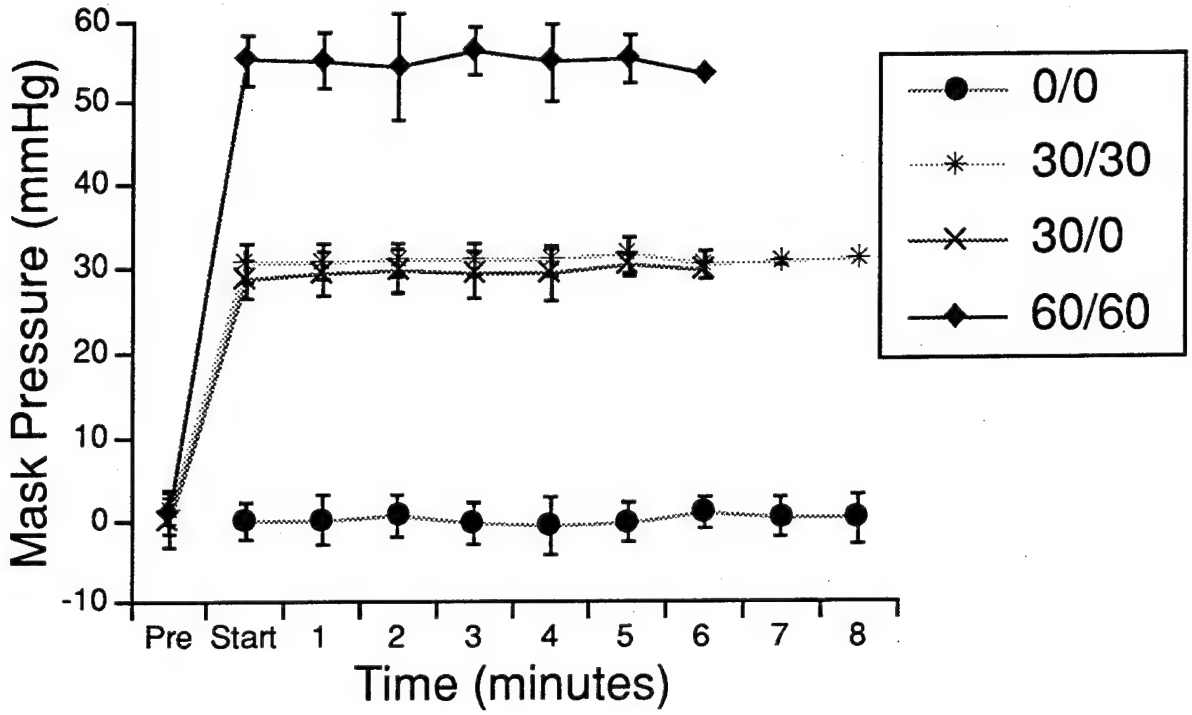


Figure 2. Mean Mask Pressure Vs Time (PPB/suit pressure).

Ventilatory, Metabolic and Blood Gas Measurements

There was a significant effect of PPB pressure on $\dot{V}_E$ ($P < .0001$). Individual paired comparisons indicated that each of the three pressure conditions was significantly different from zero mask pressure ($P < .05$). There was no significant effect of breathing gas or altitude on minute ventilation.

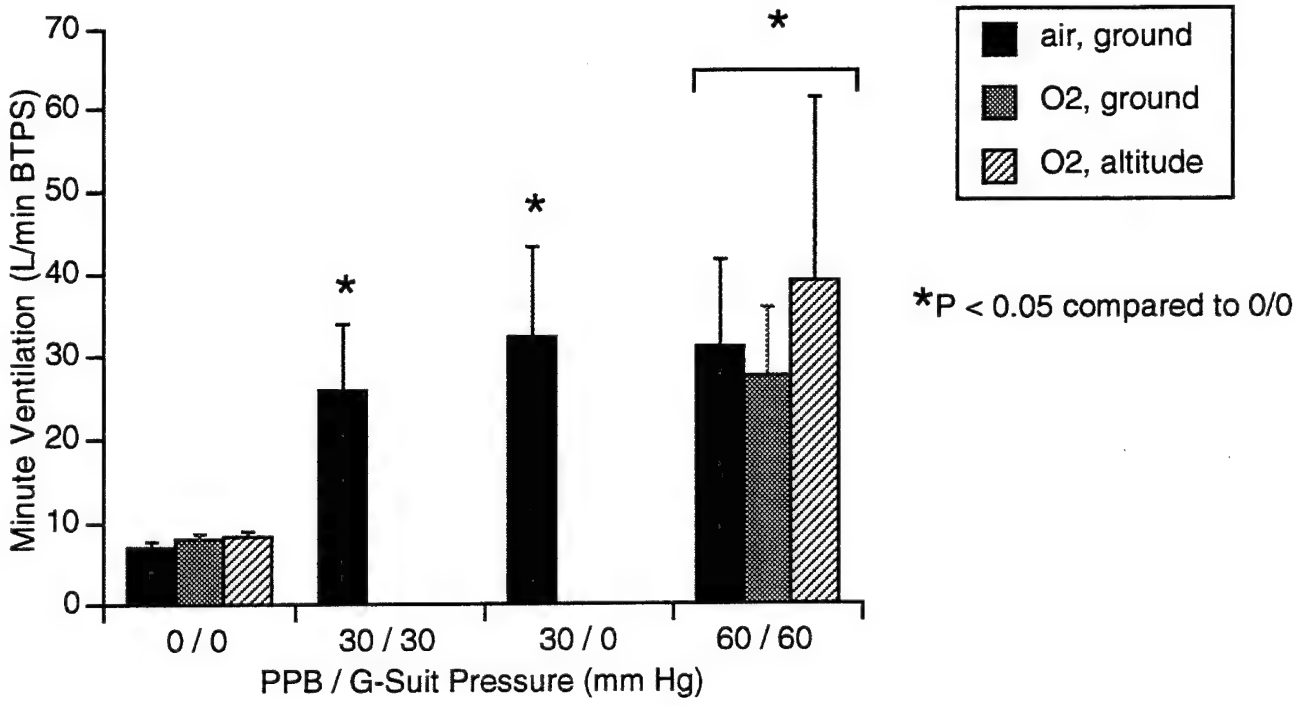


Figure 3. Minute Ventilation Vs Condition.

The following figure (Fig. 4) shows no significant effect of pressure condition on oxygen uptake.

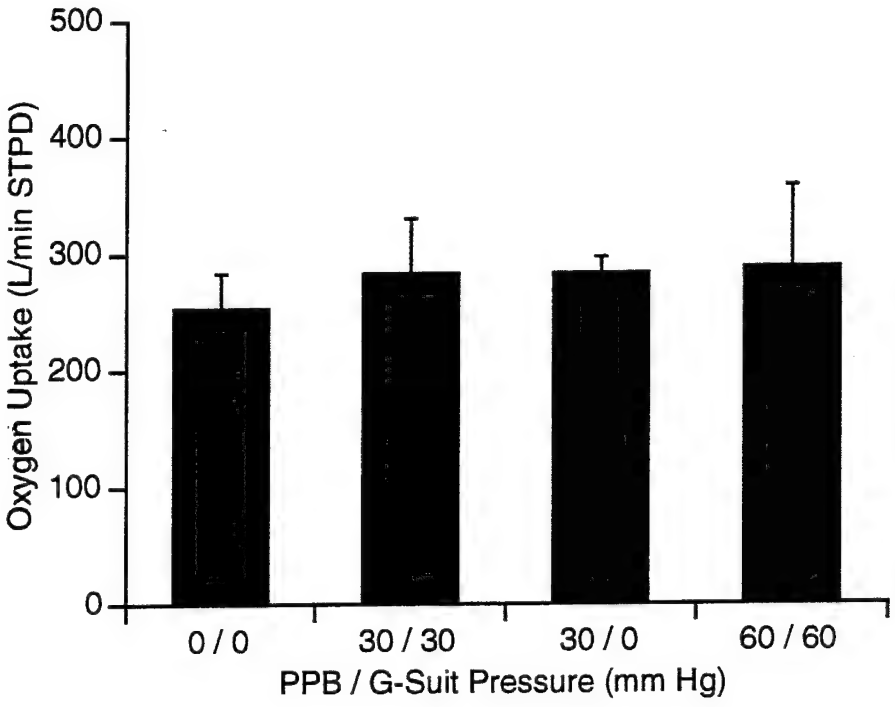


Figure 4. Oxygen Consumption Vs Condition.

Fig. 5 shows that carbon dioxide elimination rate increased significantly under all conditions of increased mask pressure ($P < .0001$). Each of the conditions with increased mask pressure was significantly different from zero mask pressure ($P < .05$). The increased carbon dioxide elimination mostly represents the effects of acute hyperventilation, rather than increased metabolic carbon dioxide production. There was no significant effect of breathing gas or altitude on carbon dioxide elimination.

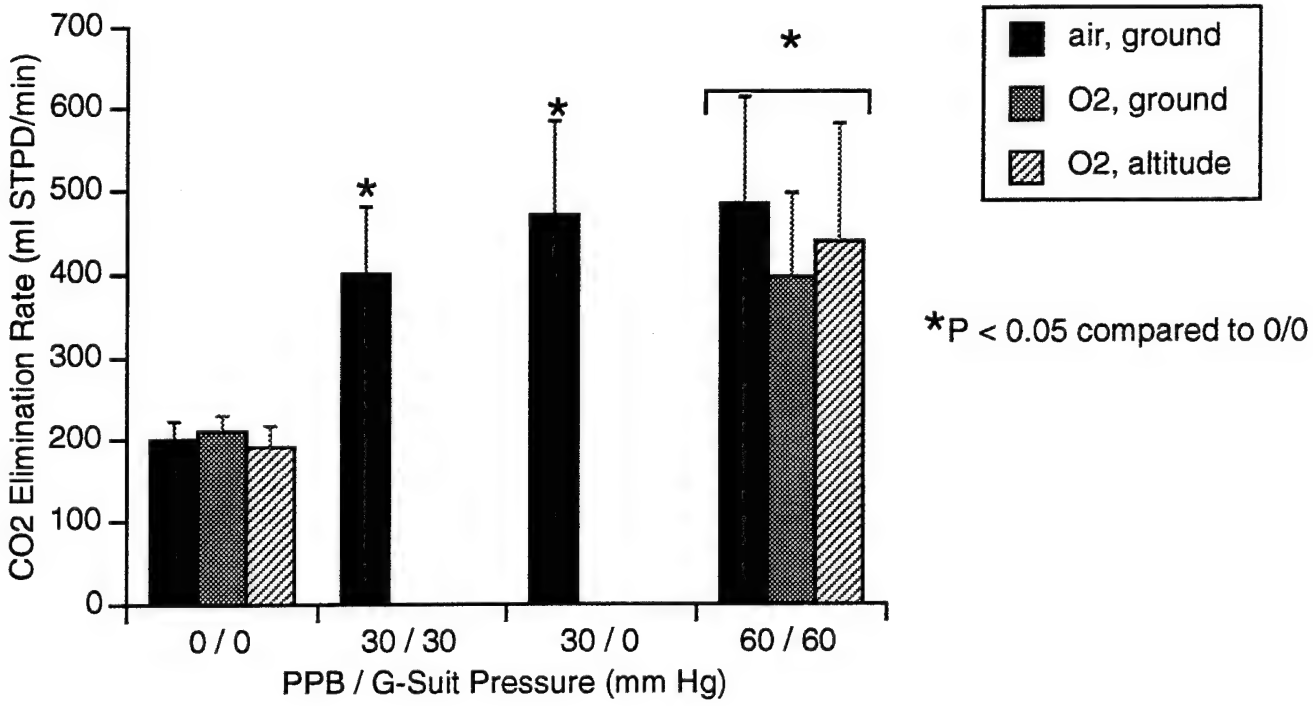


Figure 5. Carbon Dioxide Elimination Rate Vs Condition.

Increased mask pressure resulted in a significant reduction in arterial PCO_2 ($P < .0001$). Each of the increased mask pressure conditions was significantly different from zero mask pressure. There was no significant effect of breathing gas or altitude on arterial PCO_2 (Fig. 6).

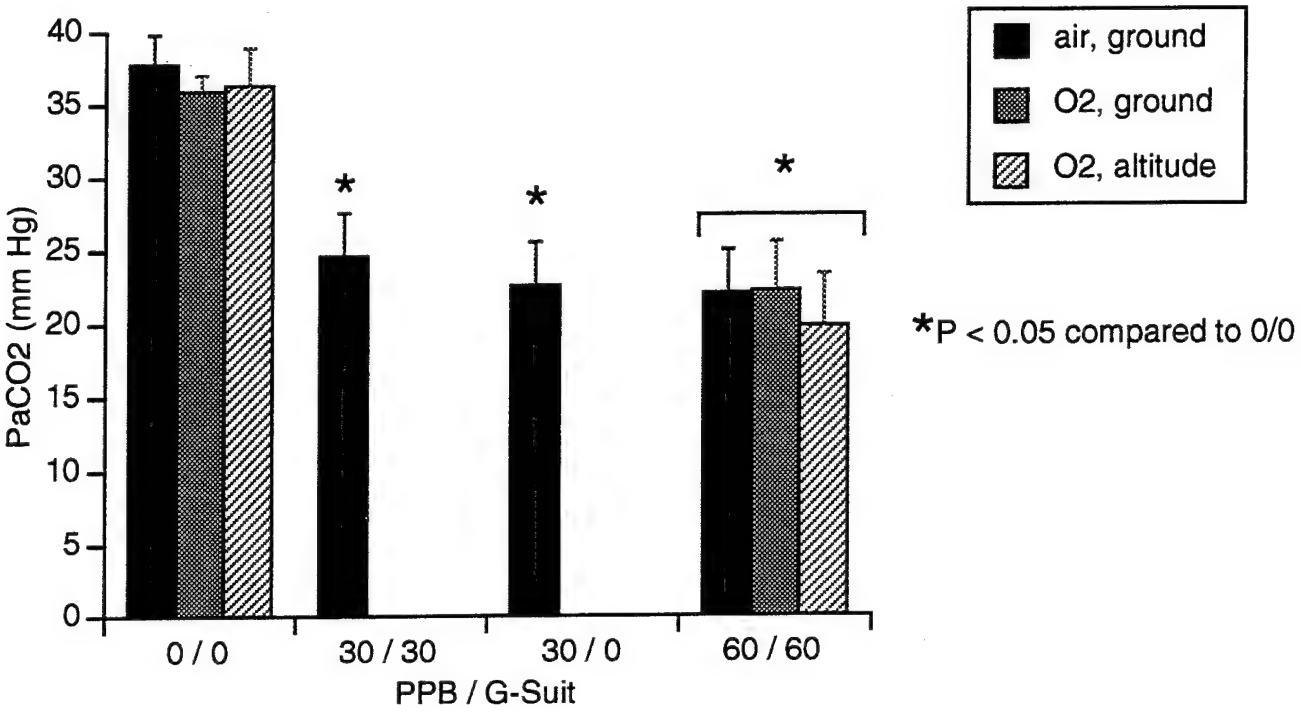


Figure 6. $PaCO_2$ Vs Condition.

Increased mask pressure resulted in significant increase in arterial pH ($P < .0001$) (Fig. 7). Each of the increased mask pressure conditions was significantly different from zero mask pressure ($P < .05$). There was no significant effect of altitude or breathing gas on arterial pH. The change in arterial pH was entirely due to the effects of reduced arterial PCO_2.

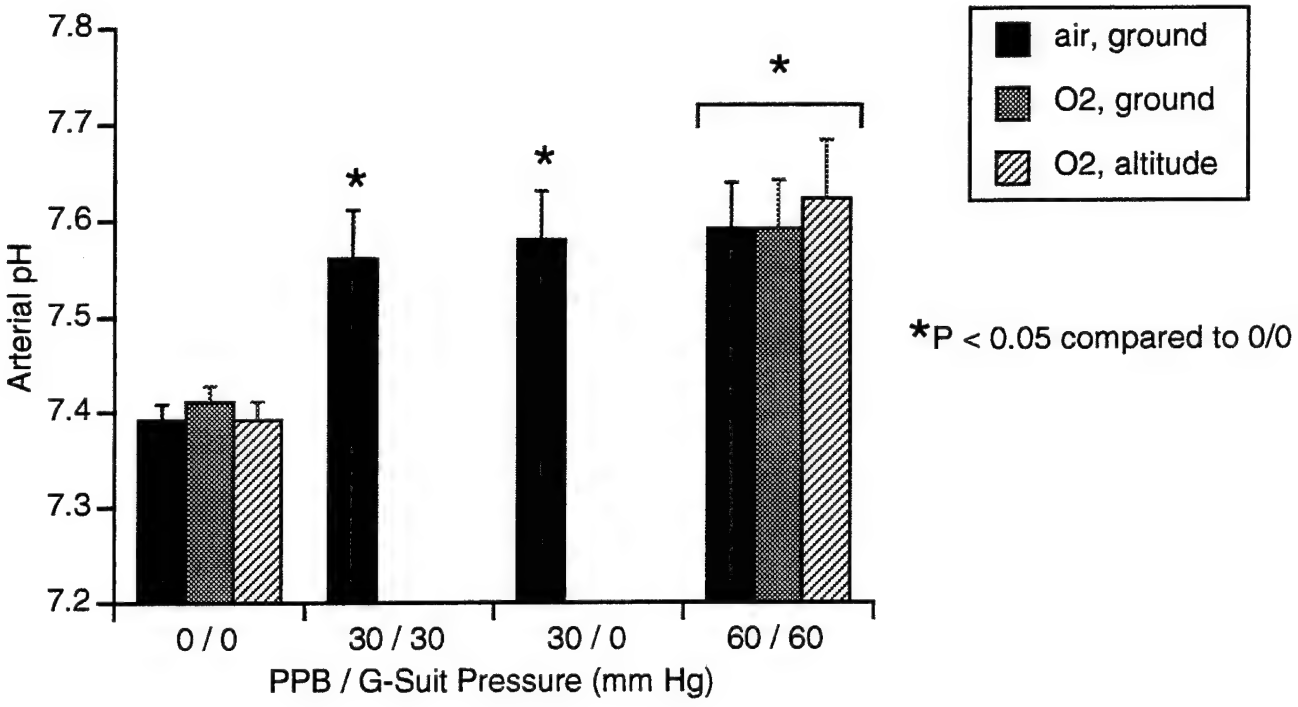


Figure 7. Arterial pH Vs Condition.

Both breathing gas and altitude significantly affected arterial oxygen tension ($P < .0001$) (Fig. 8). As expected from the alveolar gas equation, reduction in arterial PCO_2 during PPB was associated with a rise in PO_2 ($P < .0001$).

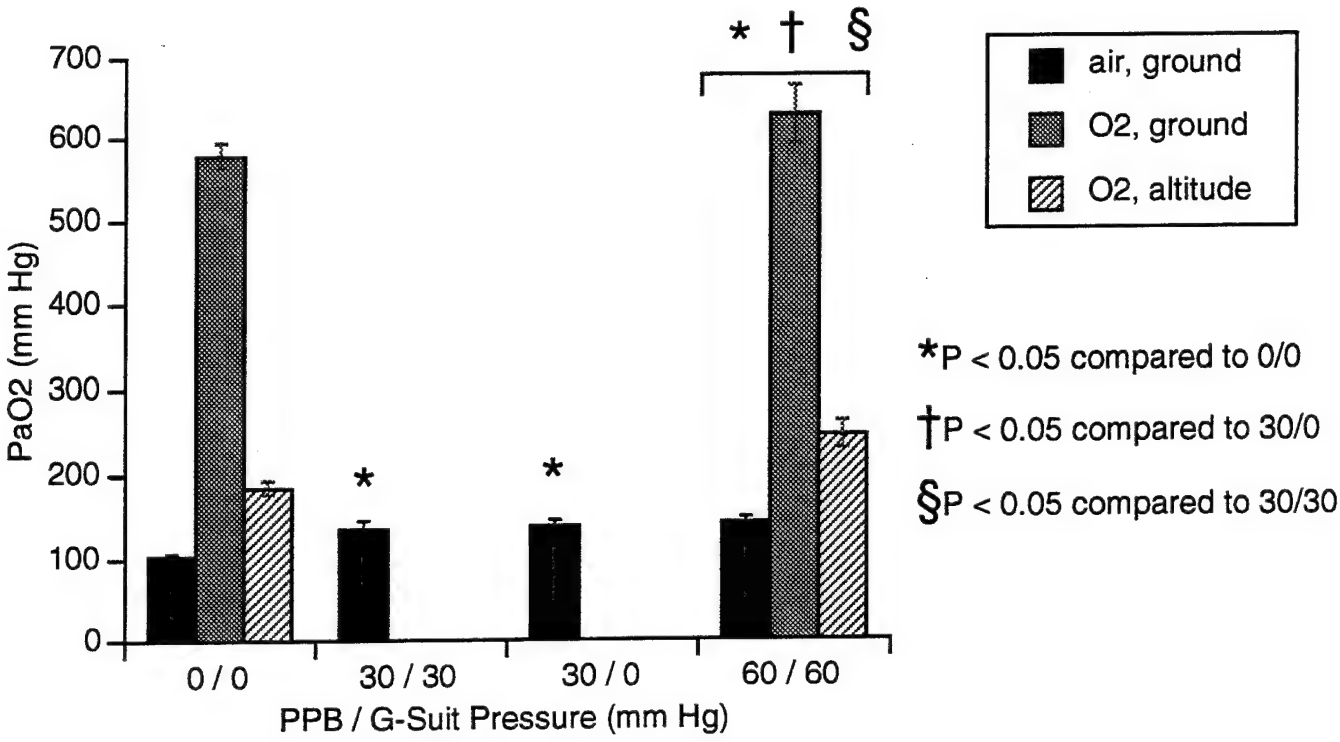


Figure 8. PaO_2 Vs Condition.

Pulmonary Gas Exchange Efficiency Measurements

Bohr V_D/V_T ratio increased at altitude compared to ground level ($P < .025$). However, when V_D/V_T was adjusted for mask pressure there was no significant effect of altitude (Fig. 9). There was no significant effect of either breathing gas or mask pressure on V_D/V_T. However, Fig. 10 shows that increasing mask pressure resulted in a significant increase in tidal volume ($P < .0001$). There is no effect of mask pressure on ventilatory frequency, although two individuals became tachypneic toward the end of the 60 mm PPB runs with ventilatory rates in the 40's, consistent with respiratory muscle fatigue (see Fig. 27).

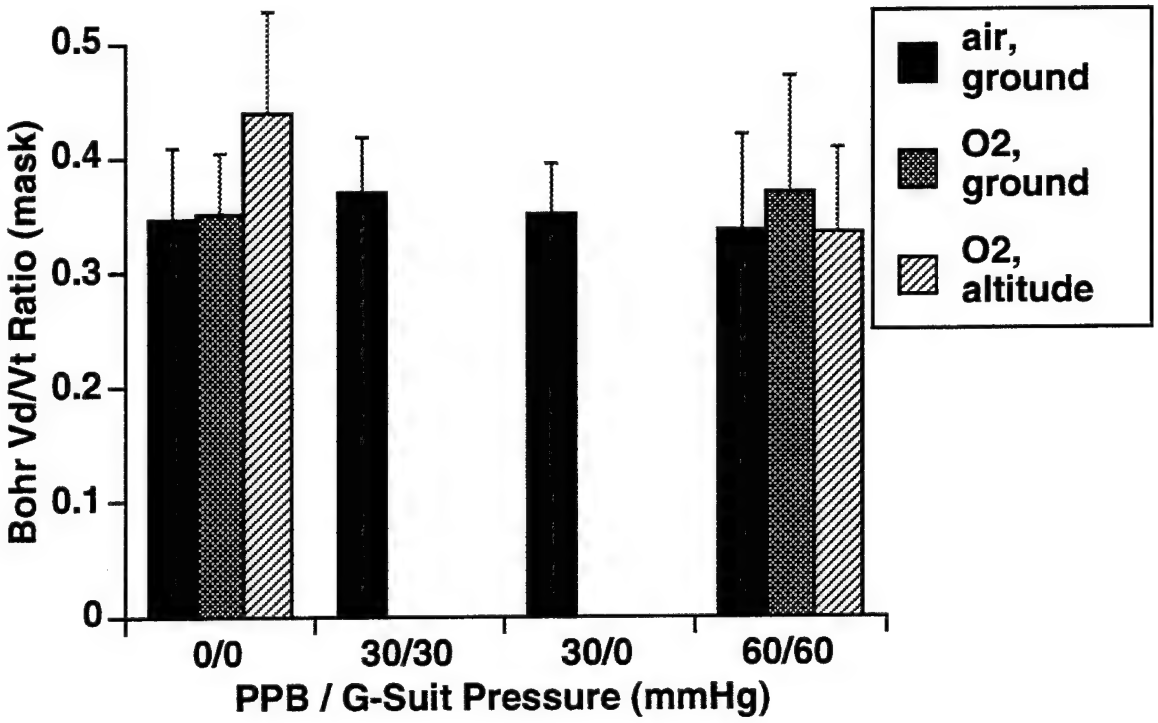


Figure 9. Bohr Vd/Vt Ratio (Mask Pressure) Vs Condition.

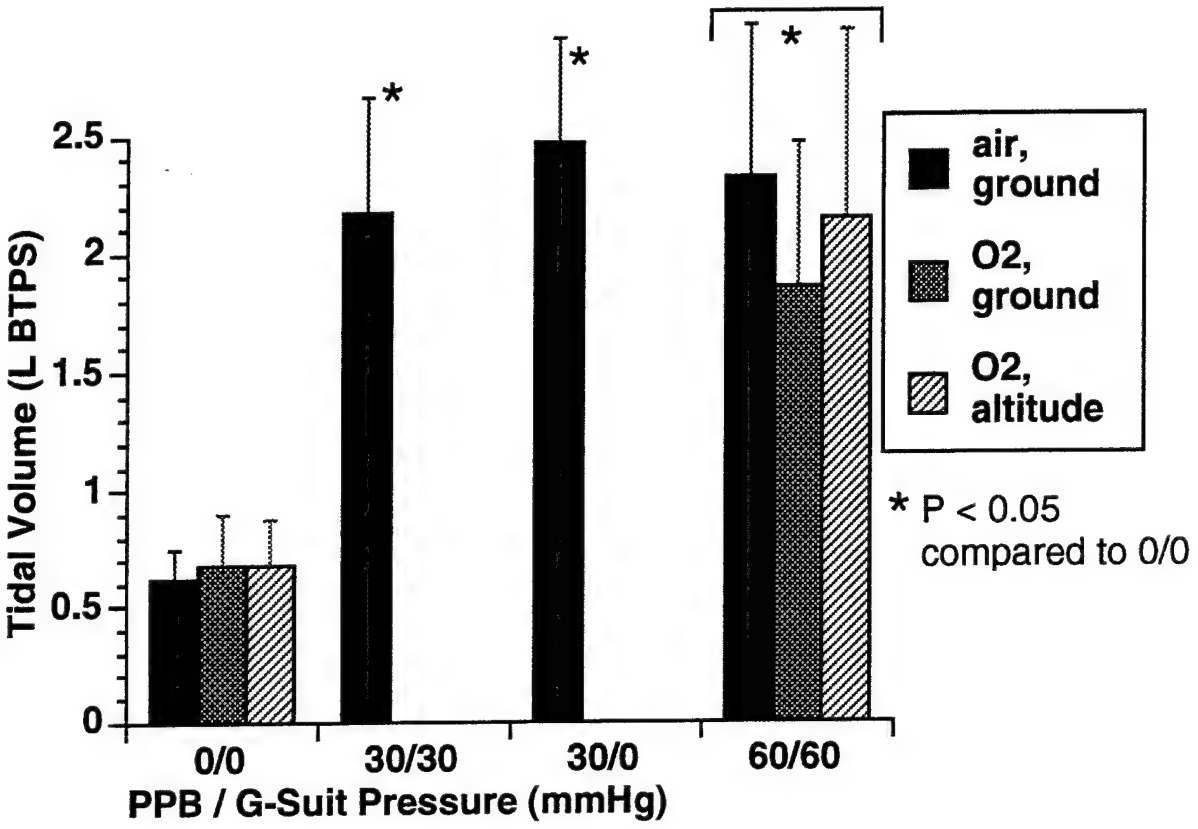


Figure. 10. Tidal Volume Vs Condition.

Dead space calculated by the Enghoff modification of the Bohr equation significantly increased with increasing mask pressure ($P < .0001$). All three conditions of increased mask pressure were significantly different from zero mask pressure ($P < .05$). The increase in CO_2 dead space was due to increased tidal volume. During PPB, the unchanged V_D/V_T ratio and reduced $PaCO_2$ provide evidence that the marked hyperpnea that the subjects exhibited was not merely compensation for increased wasted (dead space) ventilation.

Absolute dead space (adjusted for mask pressure) is shown in Fig. 11.

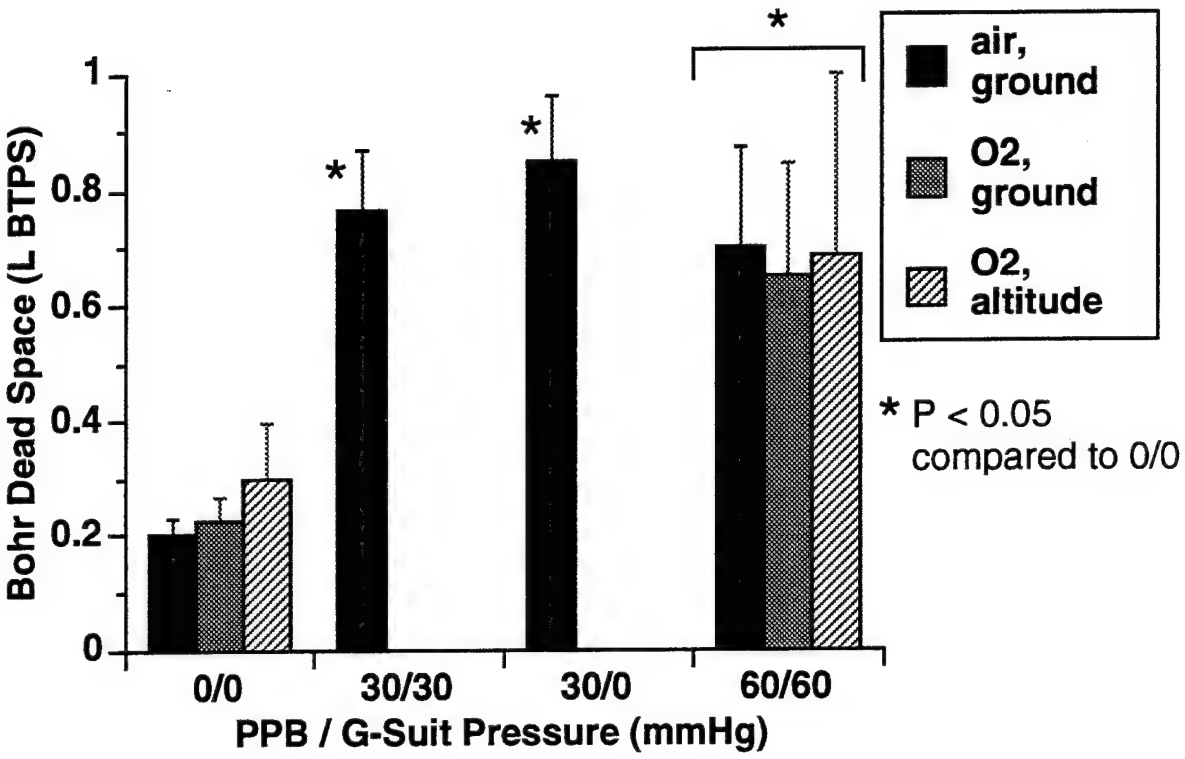


Figure 11. Bohr Dead Space Vs Condition.

Inert Gas Analysis and $\dot{V}_A/\dot{Q}$

A typical example of the 50 compartment lung model is shown in Figs. 12 and 13. On the abcissa is $\dot{V}_A/\dot{Q}$ ratio and on the ordinate is ventilation or perfusion. Both shunt and dead space are shown separately as fractions of cardiac output and tidal volume, respectively. During positive pressure breathing there is a progressive shift to the right of the $\dot{V}_A/\dot{Q}$ distribution, reflecting both perfusion and ventilation shifting to lung units with higher $\dot{V}_A/\dot{Q}$ ratios. Adjustment of mixed expired inert gas partial pressures in a manner similar to the adjustment for P_ECO_2 (see page 10) would tend to minimize these changes. Shunt is zero during air breathing. There is no effect of pressure breathing on dead space as a fraction of tidal volume. During oxygen breathing some runs were associated with a slight increase in shunt and perfusion of low $\dot{V}_A/\dot{Q}$ units. This was particularly evident at altitude, since this experimental run was preceded by at least 60 minutes of O_2 breathing. High mask pressure tended to eliminate these changes, though the effect of PPB on perfusion to units with $\dot{V}_A/\dot{Q}$ less than 0.1 did not reach statistical significance. There was, however, a significant decrease in perfusion of lung units with $\dot{V}_A/\dot{Q}$ ratio between 0.1 and 1.0. The changes in $\dot{V}_A/\dot{Q}$ during O_2 breathing and at altitude are similar to those seen during air breathing at ground level, although dead space was significantly increased at altitude as noted above.

Though the ventilation to lung units with $\dot{V}_A/\dot{Q}$ ratio > 1 tended to increase at increased mask pressure there was no significant effect on dead space. This is confirmed by the fact that $DISP_E$ was not significantly effected by any of the independent variables, including mask pressure. This same type of adjustment for mask pressure could be performed on the inert gas measurements. This would serve only to further minimize the statistically significant but relatively small physiological changes.

Increased mask pressure induced a shift of perfusion and ventilation to higher $\dot{V}_A/\dot{Q}$ units. Higher mask pressure also induced an increase in the log standard deviation of the perfusion distribution. At 60 mmHg mask pressure this parameter increased approximately two-fold while breathing air at ground level and about 50% at altitude.

$\dot{V}_A/\dot{Q}$ was also affected by altitude. At altitude there was increased perfusion of lung units with low $\dot{V}_A/\dot{Q}$ and shunt and also increased ventilation of high $\dot{V}_A/\dot{Q}$ units and dead space. Because of the necessity of oxygen pre-breathing it is impossible to exclude the fact that these changes may have represented the cumulative effect of 100% oxygen breathing rather than altitude *per se*.

A six compartment collation of the 50 compartment lung model is shown in Fig.14. As in Figs. 12 and 13 positive pressure breathing results in a "shift to the right" to high $\dot{V}_A/\dot{Q}$ units.

Log dispersion of ventilation and perfusion is shown in Fig. 15. These indices are calculated to reflect $\dot{V}_A/\dot{Q}$ mismatching in the main body of the $\dot{V}_A/\dot{Q}$ distribution. Positive high mask pressure resulted in a significant increase in $\dot{V}_A/\dot{Q}$ mismatching as reflected by an increase in $\log SD_{\dot{Q}}$ ($P < .0001$).

FIGURE 12. VENTILATION-PERFUSION DISTRIBUTION: SUBJECT RT, GROUND LEVEL, AIR BREATHING

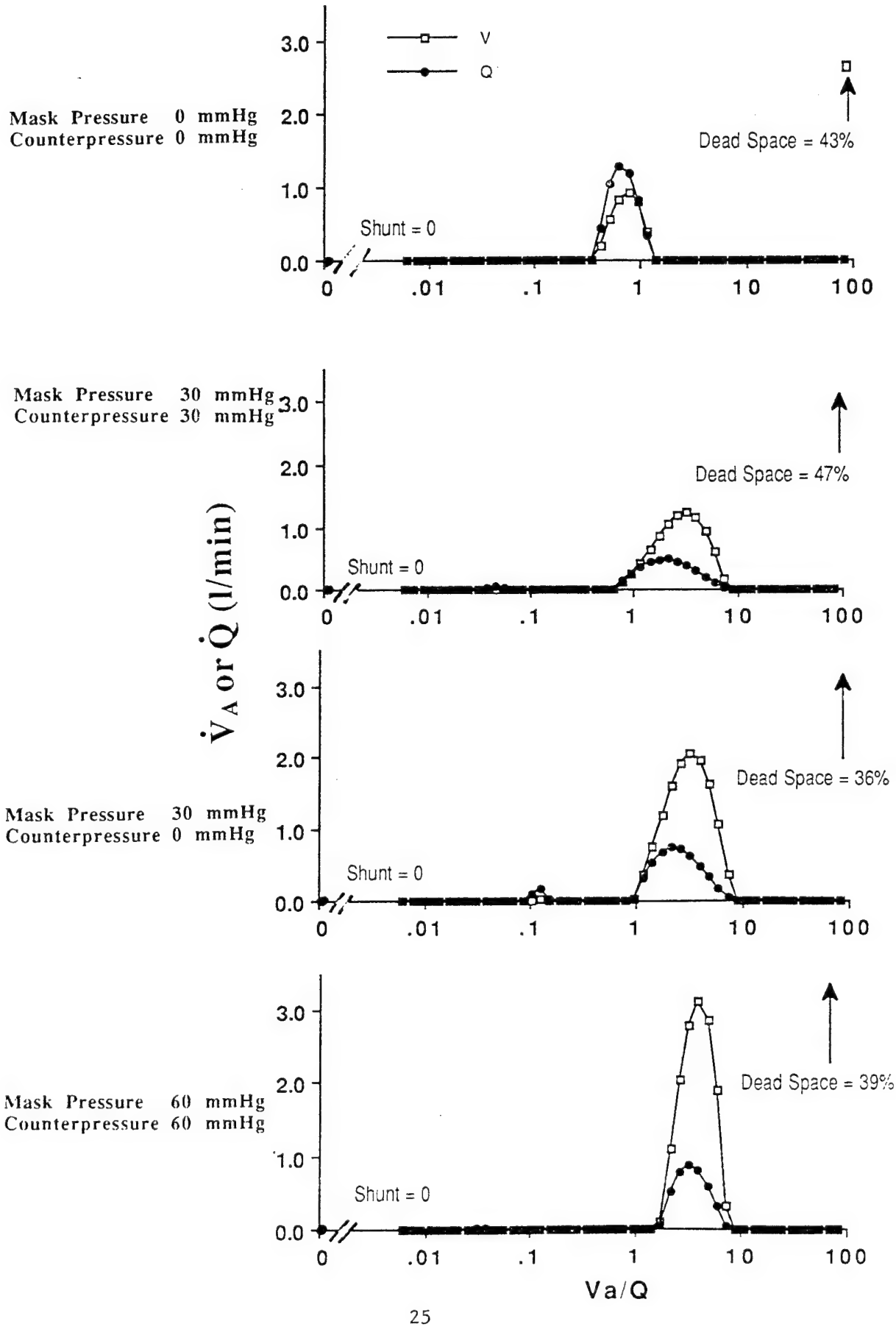
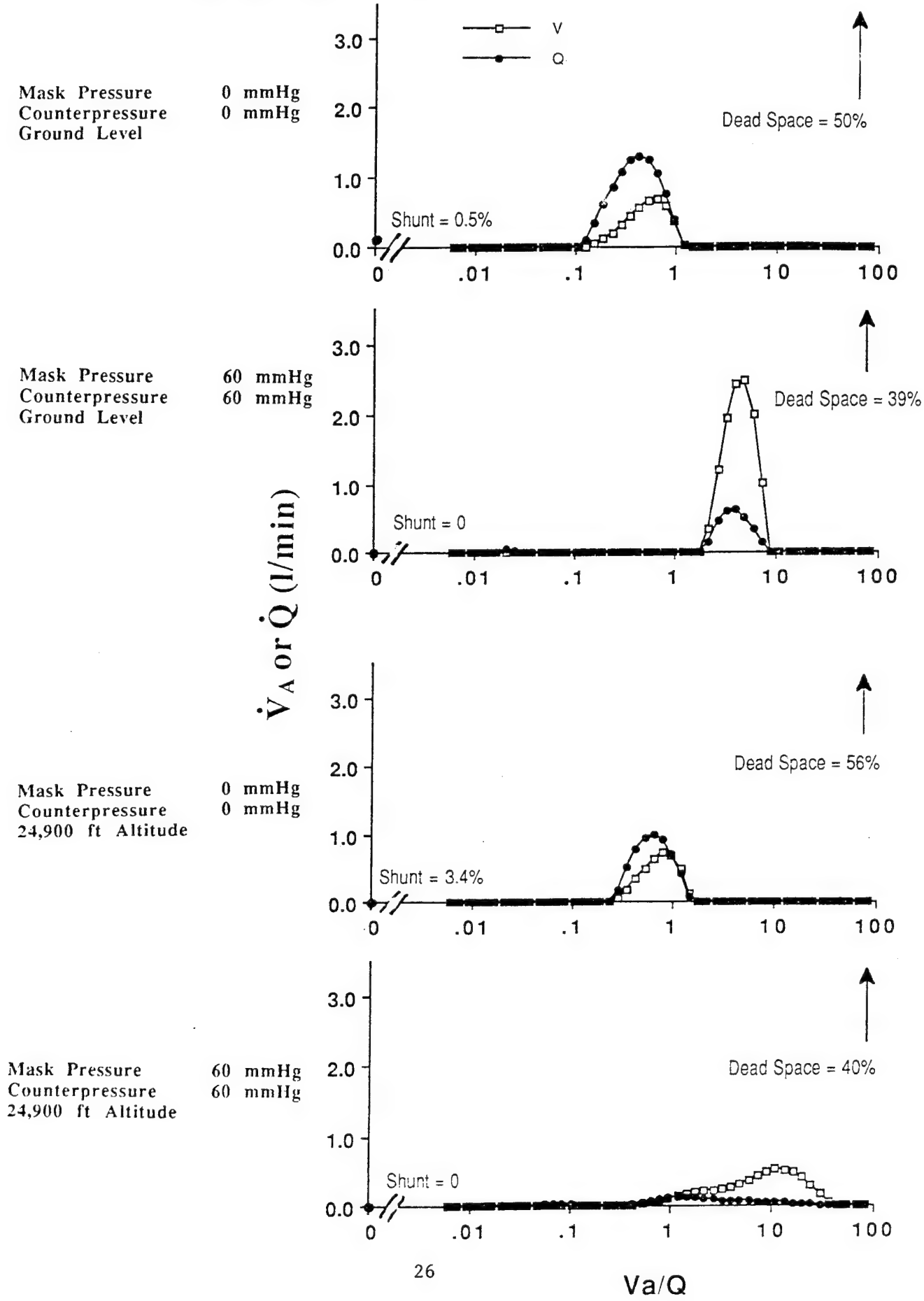


FIGURE 13. VENTILATION-PERFUSION DISTRIBUTION: SUBJECT RT, OXYGEN BREATHING



$\dot{V}_A/\dot{Q}$ Multiple Inert Gases Summary (Air Breathing)

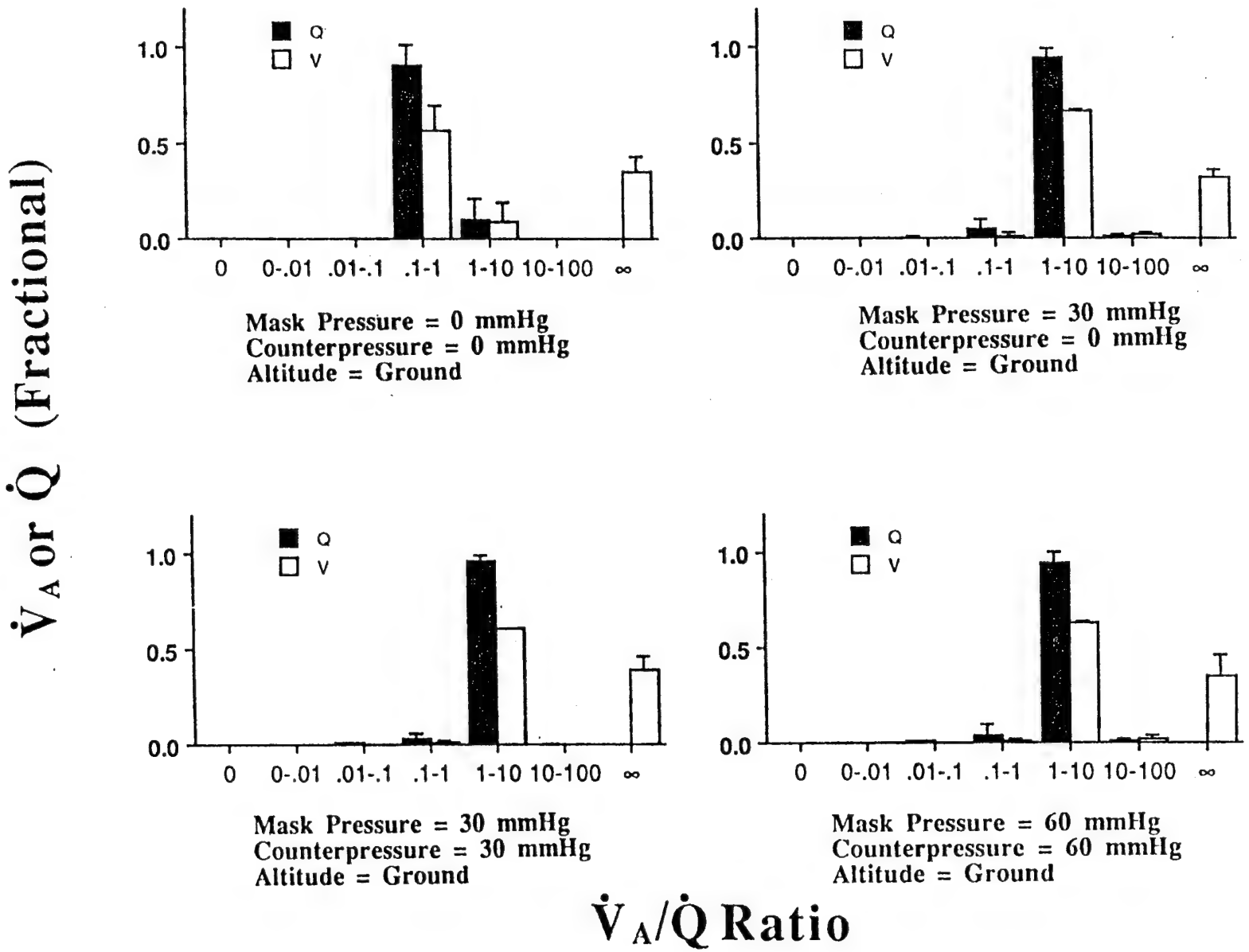


FIG. 14A

$\dot{V}_A/\dot{Q}$ Multiple Inert Gases Summary (O_2 Breathing)

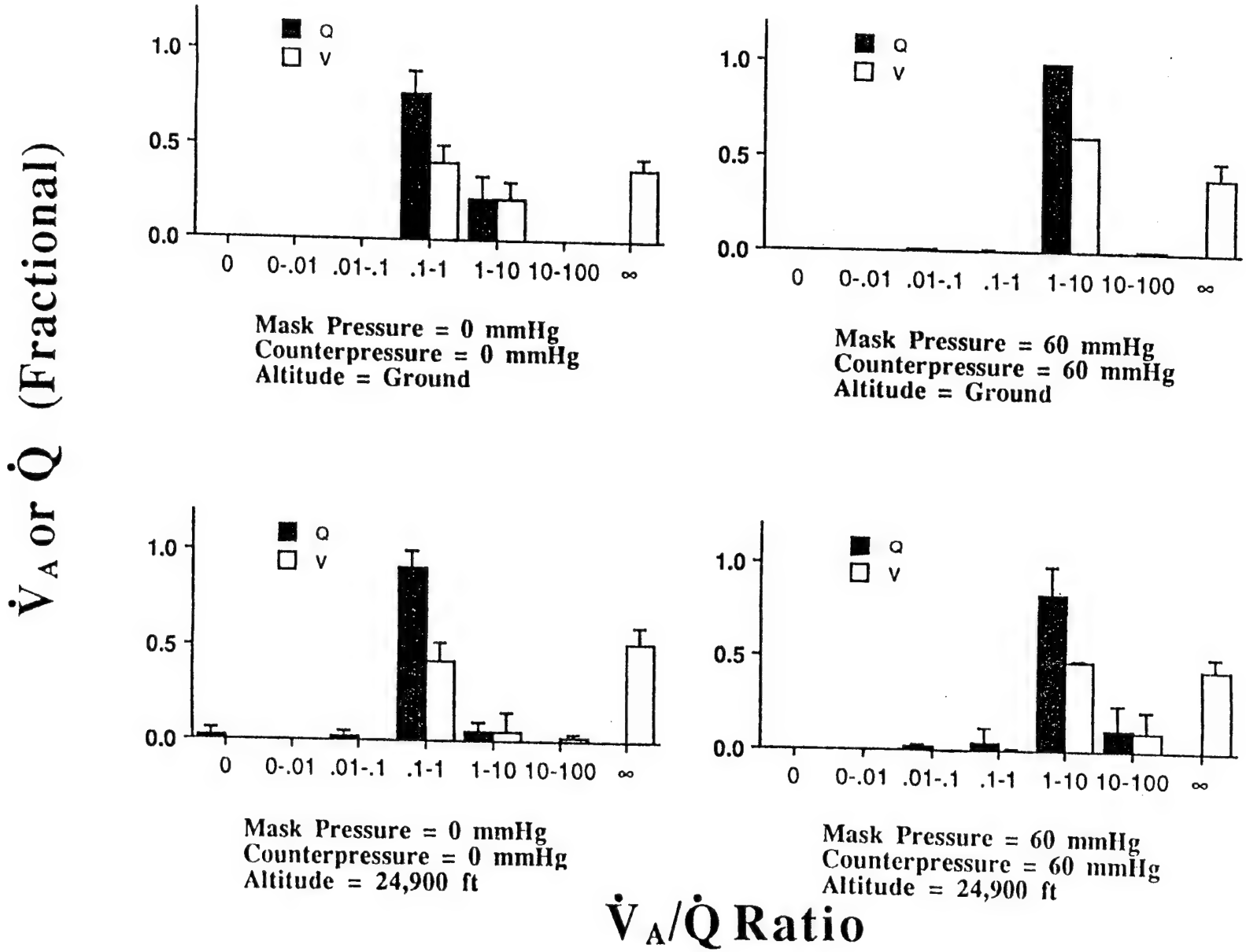
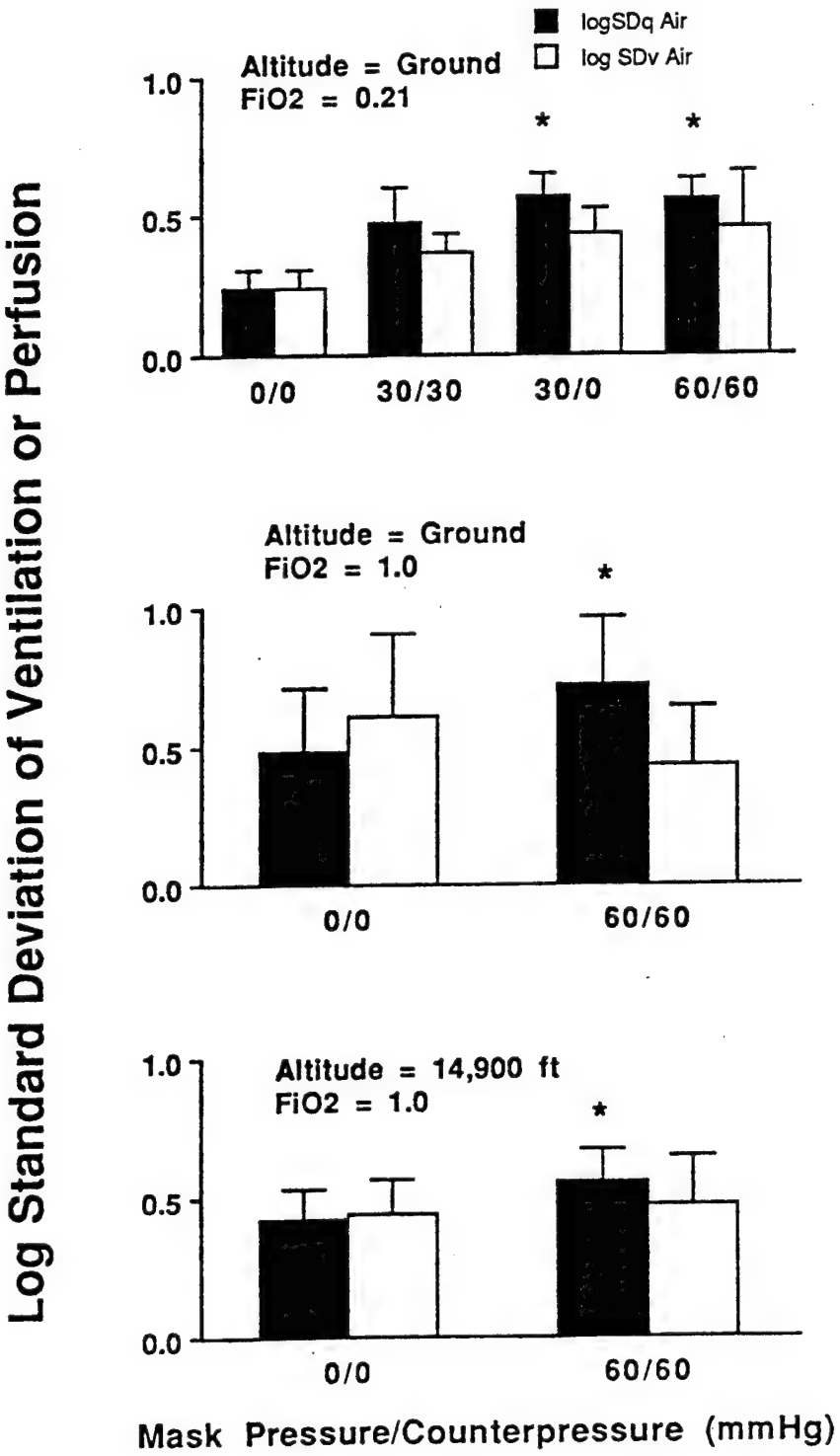


FIG. 14B

Log Dispersion of Ventilation and Perfusion



* P < .05 Compared to 0/0

FIG. 15

Hemodynamic Measurements

Minute-by-minute trends of the various hemodynamic variables are plotted to Figures 16 to 18 and 20 to 22 for air runs. Statistical comparisons are summarized in Tables 4 to 6. The oxygen runs showed similar trends.

Fig. 16 shows the progressive increase in heart rate with increasing mask pressure ($P < .0001$). Heart rate at each of the increased mask pressure conditions was significantly different from the zero mask pressure condition ($P < .05$). Two subjects demonstrated a bradycardia associated with inability to maintain pulse pressure and mean arterial pressure prior to terminating the 60/60 mm Hg run.

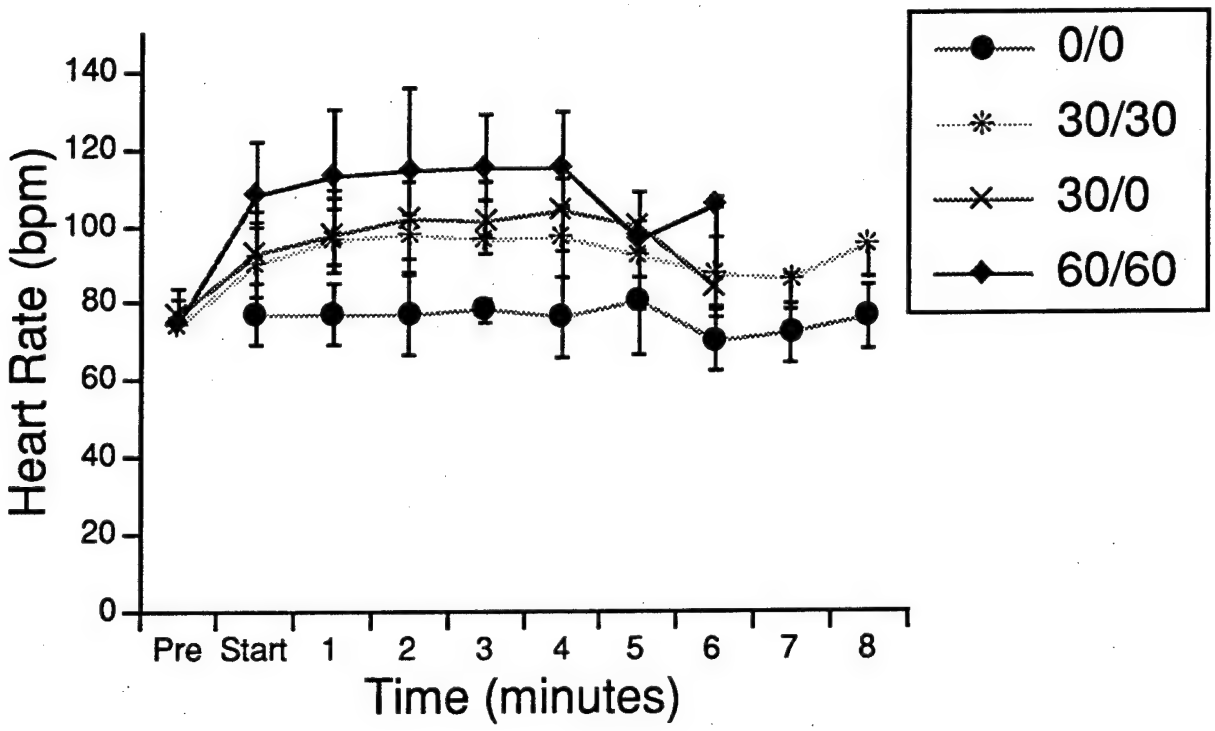


Figure 16. Heart Rate Vs Time (PPB/suit pressure).

Fig. 17 shows that mean arterial pressure progressively increased with the increasing mask pressure ($P < .0001$).

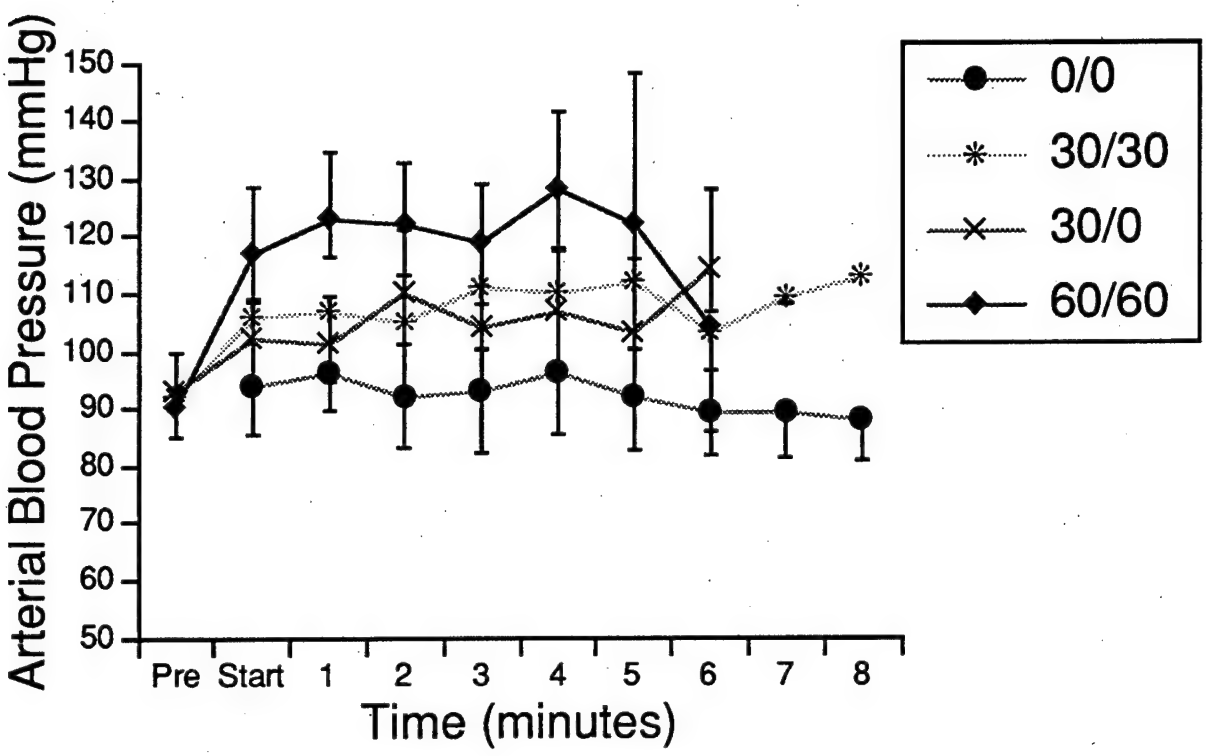


Figure 17. Arterial Blood Pressure Vs Time (PPB/suit pressure).

Despite the elevated arterial pressure, pulse pressure progressively decreased with duration of the experiment run (P = .019) (Fig. 18). The progressive reduction in pulse pressure most likely represented the cumulative effect of reduced venous return over time. In some individuals this resulted in reduced cardiac output and evidence of reduced cerebral blood flow, manifested by loss of consciousness.

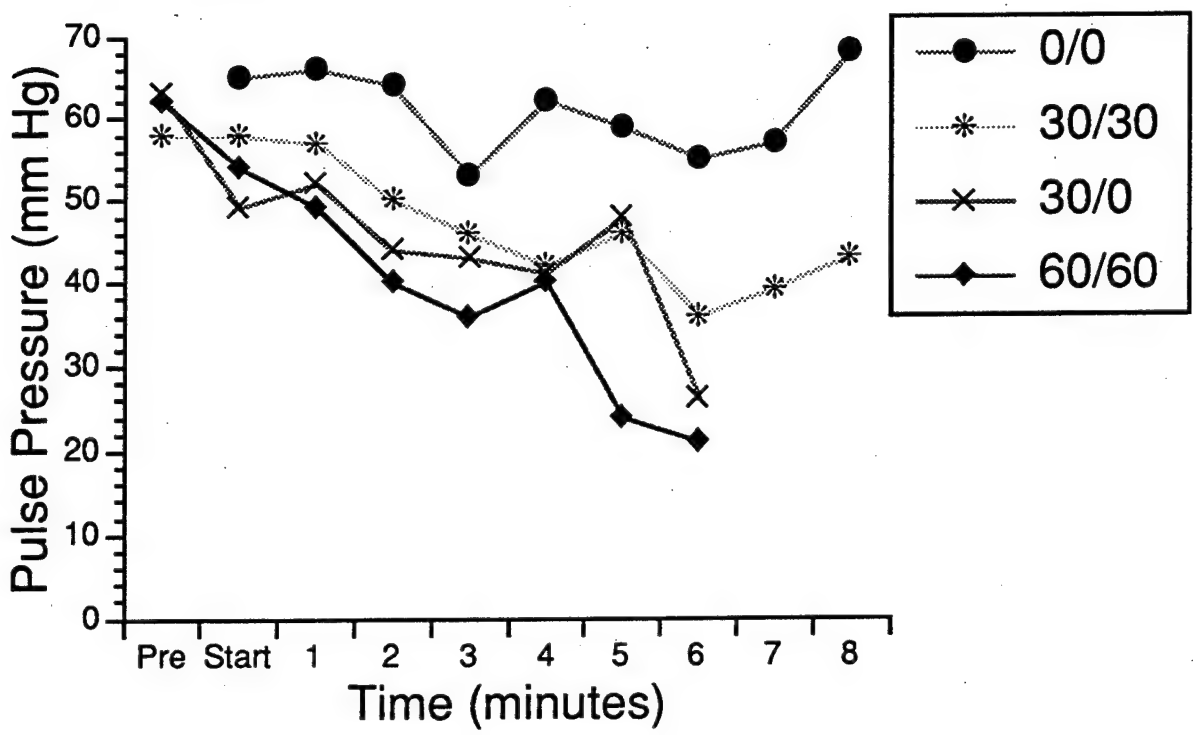


Figure 18. Arterial Pressure Vs Time (PPB/suit pressure).

The high mask pressure runs were associated with a cyclical variation in blood pressure in concert with respiratory movements. Fig. 19 shows the raw data from one of the 60 mm Hg runs. The top tracing is the arterial blood pressure and the bottom tracing is the mask pressure. Both the absolute values of the blood pressure as well as the difference between systolic and diastolic pressure (pulse pressure) varies with mask pressure. This probably represented pulsatile changes in venous return during the respiratory cycle.

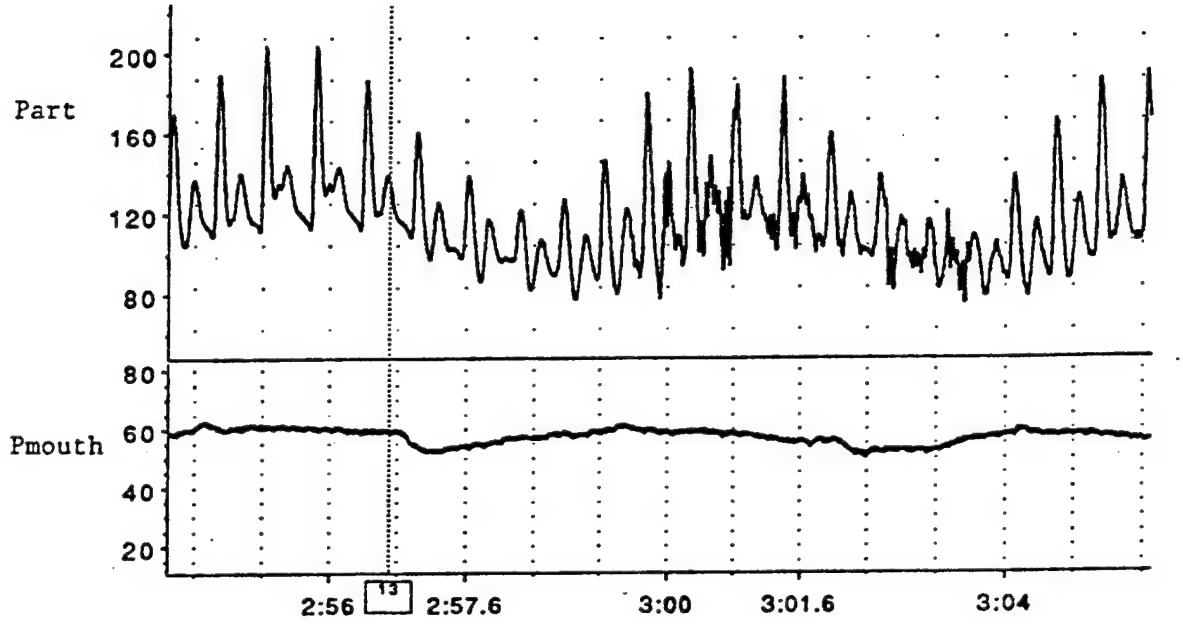


FIGURE 19. Example of cyclical variation in arterial pressure during 60 mmHg pressure exposure. SB breathing air at ground level.

Figs. 20 and 21 depict the respiratory variation in pulse pressure as a function of time. The gradual reduction in both "maximum" (top point) and "minimum" (bottom point) pulse pressure observed during expiration and inspiration, respectively, is shown. There is no trend with time when mask pressure is zero (Fig. 21). There is a progressive decrease in both the maximum and minimum pulse pressures during a breathing cycle at 60 mm mask pressure as the run progresses (Fig. 20).

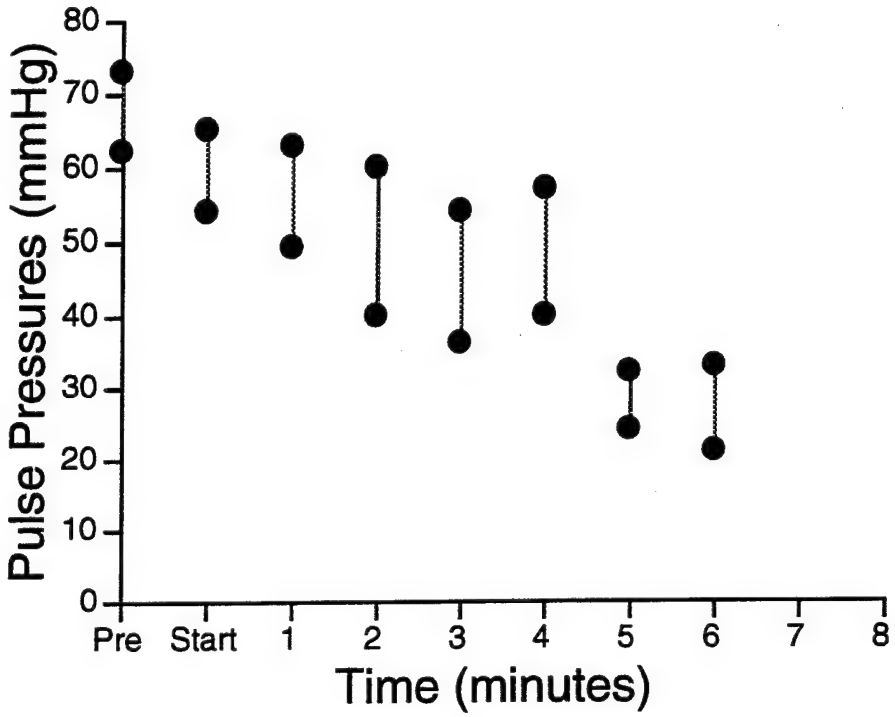


Figure 20. Respiratory Variation In Pulse Pressure Vs Time (60/60).

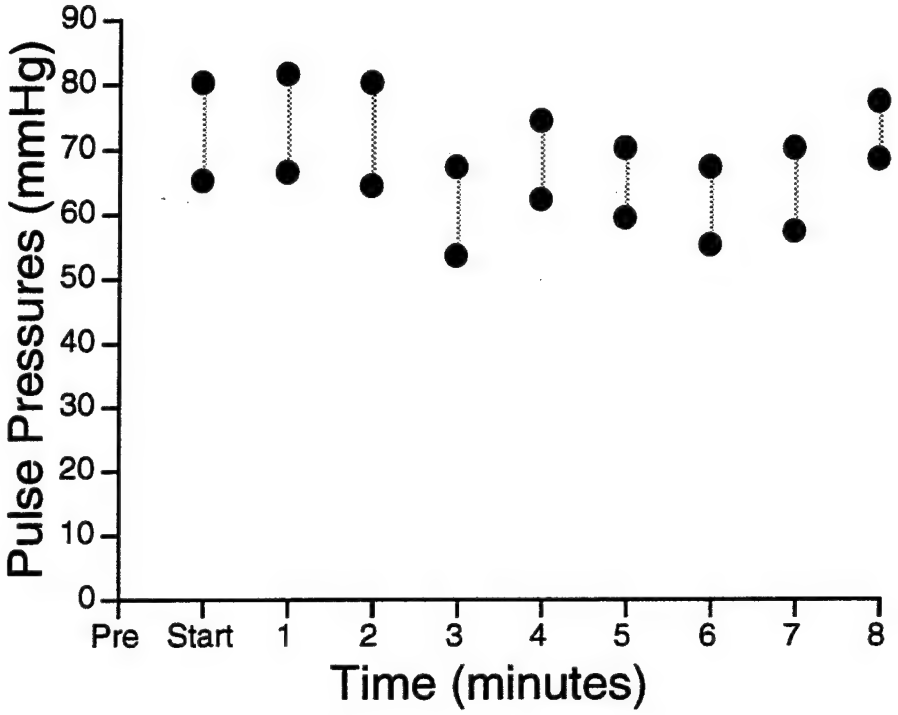


Figure 21. Respiratory Variation In Pulse Pressure Vs Time (0/0).

Increased mask pressure resulted in an increase in CVP (P = .0001) (Fig. 22). This increase in CVP is in part due to the increased intrathoracic pressure. Pulmonary artery wedge pressure shows a similar trend and was generally around 5 mmHg higher than CVP. However, is it also possible that the catheter tip was lodged in a relatively under-perfused lung unit, especially during high mask pressures, and therefore may not have represented left atrial pressure.

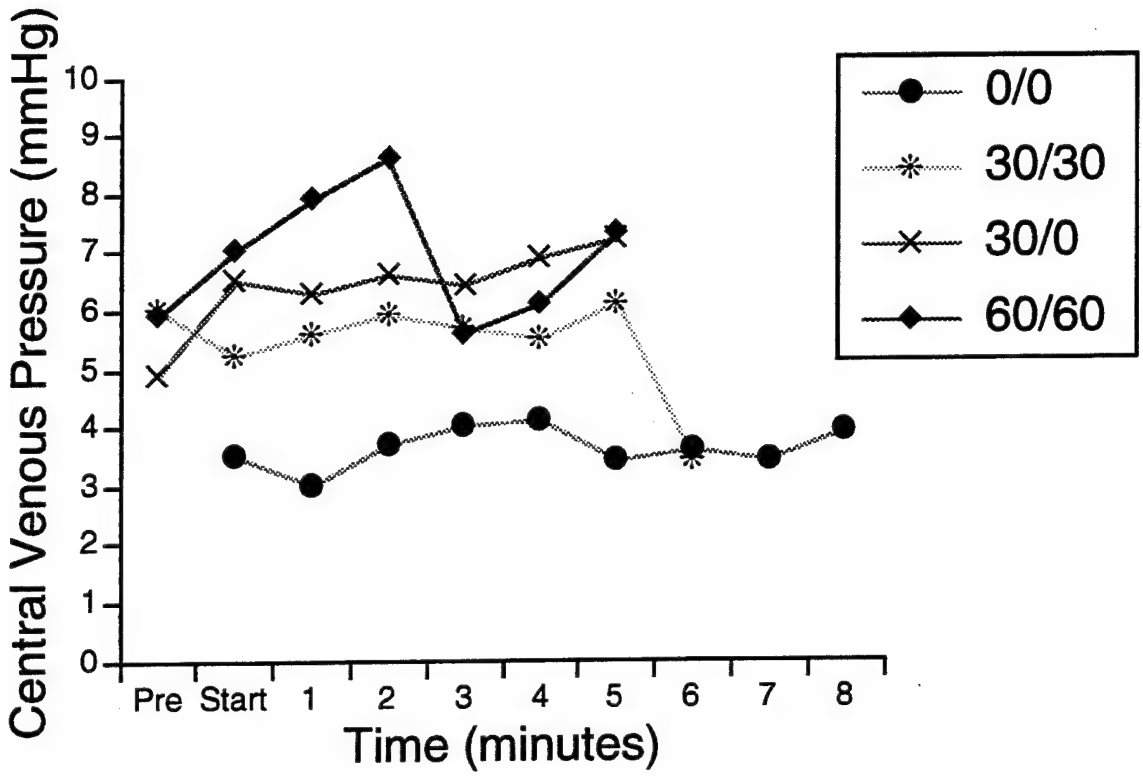


Figure 22. CVP Vs Time.

Increase in mask pressure resulted in reduced cardiac output (P = .03 by MIG and O_2 Fick) (Fig. 23). Oxygen Fick cardiac outputs obtained during air breathing runs showed the same trend. There was more variability in thermodilution cardiac output because the value depended very highly upon the actual phase of respiration at which the injection of iced saline was made.

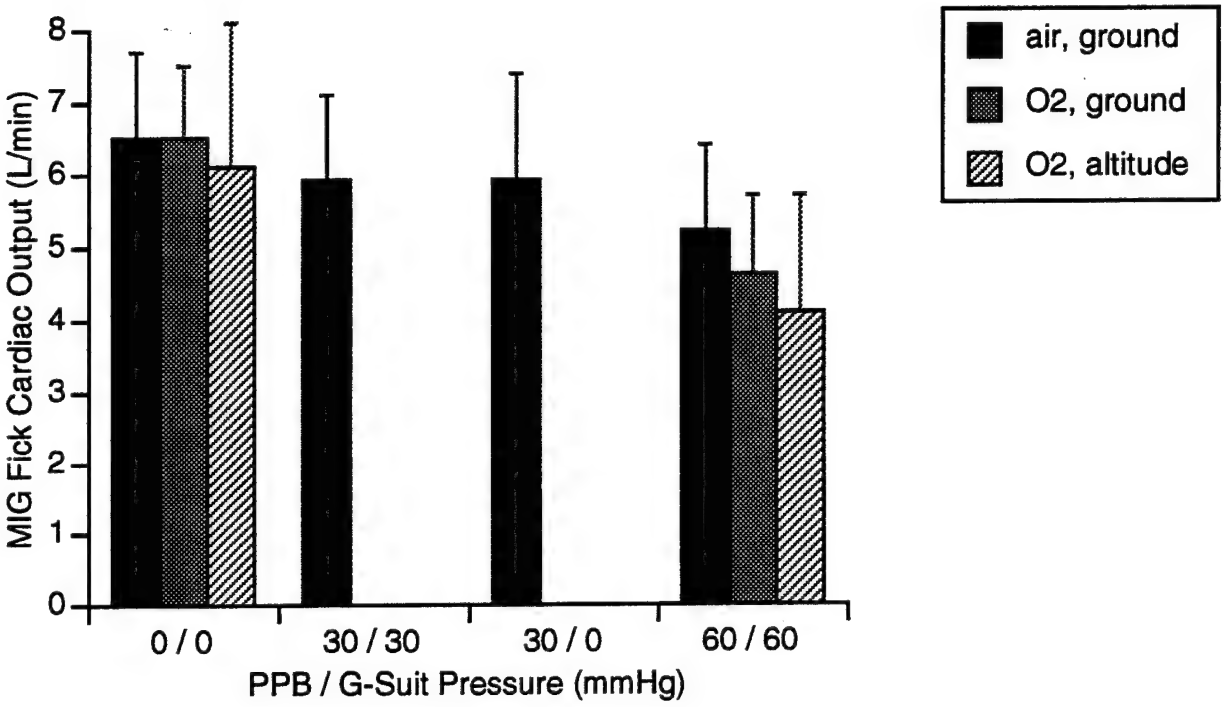


Figure 23. MIG Fick Cardiac Output Vs Condition.

Along with a reduction in cardiac output was an expected decrease in $S\bar{v}O_2$ ($P < .0001$) (Fig. 24). $S\bar{v}O_2$ was also affected by both altitude and breathing gas, since both indices affect the inspired PO_2 tension.

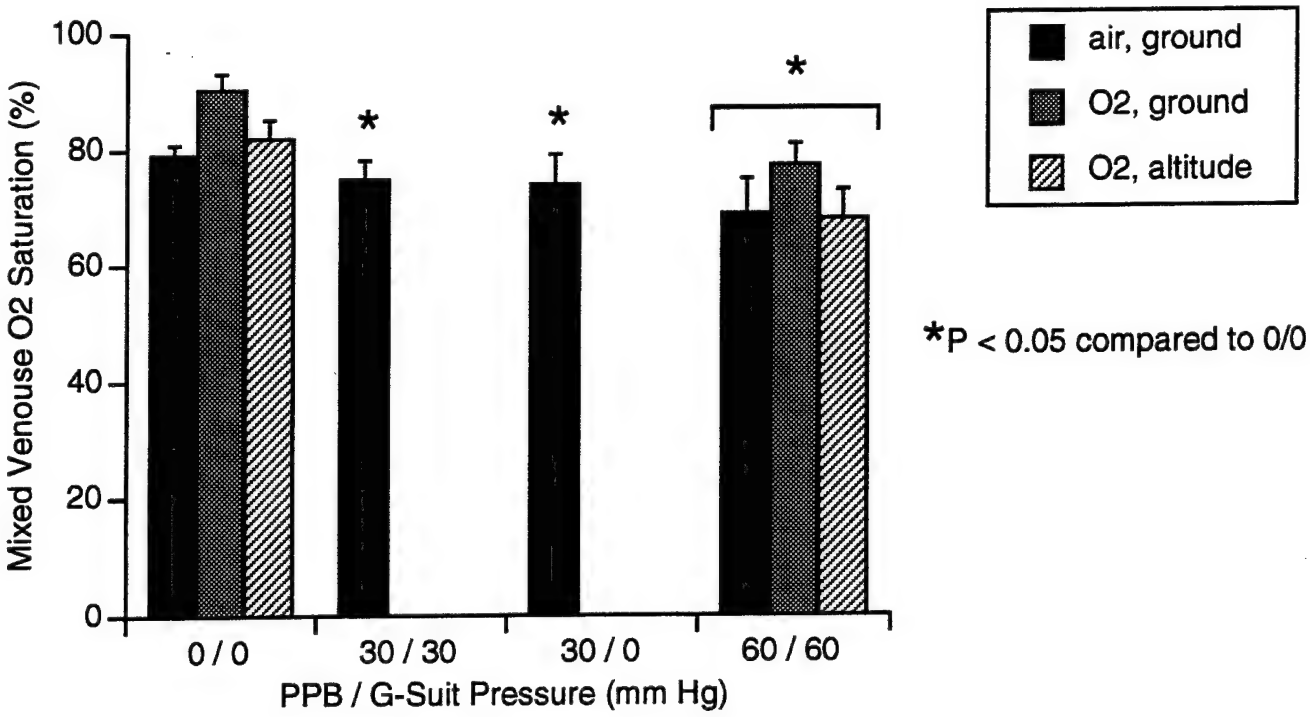


Figure 24. Mixed Venous Oxygen Saturation Vs Condition.

Statistics

Matrices of probability values obtained from ANOVA are shown in Tables 4-6.

Duration of Pressure Breathing

Experiment duration is shown in Table 7. Mean experimental run duration at zero mask pressure, indicating the time necessary to obtain all blood samples and hemodynamic measurements, was 12-13 minutes. Experimental duration was reduced to around 8 minutes at 30 mmHg and 4.5 minutes at 60 mmHg mask pressure. In part this shortened time was created by the experimenters, and was due to a reduced number of blood samples and shorter collection times, instituted because of subject stress. The collection of samples was adjusted in order to obtain at least one set of measurements in case the subject halted prematurely. Potential problems at 60 mmHg could often be predicted by observing the subject's ease at performing PPB of 30 mmHg in those instances when 30 mmHg runs preceded the 60 mmHg runs.

TABLE 4: P VALUES - CARDIOPULMONARY MEASUREMENTS

Variable	FACTOR (ANOVA)				STATISTICALLY SIGNIFICANT COMPARISONS (P < .05)		
	Altitude	FiO_2	Mask Pressure Condition	Pressure-Altitude Interaction	30/0 vs.	30/30 vs.	60/60 vs.
Minute Ventilation ($\dot{V}_E$)	NS	NS	.0001	NS	0/0	0/0	0/0
Ventilatory Frequency (V_f)	NS	NS	NS	NS			
Tidal Volume (V_T)	NS	NS	.0001	NS	0/0	0/0	0/0
O_2 Consumption ($\dot{V}O_2$)	-	-	NS	NS			
CO_2 Elimination ($\dot{V}CO_2$)	NS	NS	.0001	NS	0/0	0/0	0/0
Arterial PO_2 (PaO_2)	.0001	.0001	.0001	NS	0/0, 60/60	0/0, 60/60	0/0, 30/0, 30/30
Arterial PO_2 ($PaCO_2$)	NS	NS	.0001	NS	0/0	0/0	0/0
Arterial pH (pHa)	NS	NS	.0001	NS	0/0	0/0	0/0
Mixed Venous O_2 Saturation ($S\bar{v}O_2$)	.0001	.0001	.0001	NS	0/0	0/0	0/0
CO_2 V_D/V_T Ratio at $P_{Ambient}$ (V_D/V_T: P_{Amb})	.025	NS	NS	NS			
CO_2 Dead Space at $P_{Ambient}$ (V_D: P_{Amb})	.036	NS	.0001	NS	0/0	0/0	0/0
CO_2 V_D/V_T Ratio at P_{Mask} (V_D/V_T: P_{Mask})	NS	NS	NS	.058			
CO_2 Dead Space at P_{Mask} (V_D: P_{Mask})	NS	NS	.0001	NS	0/0	0/0	0/0
O_2 Fick Cardiac Output ($CO\text{-}O_2$)	-	-	.032	NS			0/0
MIG Fick Cardiac Output (CO-MIG)	NS	NS	.029	NS			0/0
Thermodilution Cardiac Output (CO-TD)	NS	NS	NS	NS			

Probability values calculated using 3-way ANOVA. Individual comparisons performed using Tukey-Kramer test.

TABLE 5: P VALUES - HEMODYNAMIC MEASUREMENTS

Variable	FACTOR (ANOVA)				STATISTICALLY SIGNIFICANT COMPARISONS (P < .05)		
	Altitude	FiO_2	Pressure Condition	Pressure-Altitude Interaction	30/0 vs.	30/30 vs.	60/60 vs.
Mouthpiece Pressure	NS	NS	.0001	NS	0/0, 60/60	0/0, 60/60	0/0, 30/0, 30/30
Heart Rate	.0084	NS	.0001	.063	0/0	0/0, 60/60	0/0
Arterial Pressure	.0043	NS	.0001	.0023	0/0, 60/60	0/0	0/0
PA Pressure	NS	NS	.0001	NS	0/0, 60/60	0/0, 60/60	0/0, 30/0, 30/30
CVP	NS	NS	.0001	NS	0/0, 60/60	0/0, 60/60	0/0, 30/0, 30/30
Systolic BP max	.0022	NS	.0051	.023		0/0	0/0
Diastolic BP max	.03	NS	.0001	NS	0/0, 60/60	0/0, 60/60	0/0, 30/0
Systolic BP min	.007	NS	NS	.014			
Diastolic BP min	NS	NS	.0001	.05		0/0	0/0
Pulse Pressure max	.056	NS	.04	NS			0/0
Pulse Pressure min	.007	NS	.0001	NS	0/0		0/0

Probability values calculated using 3-way ANOVA. Individual comparisons performed using Tukey-Kramer test.

TABLE 6: P VALUES - MULTIPLE INERT GAS MEASUREMENTS

Variable	FACTOR (ANOVA) Altitude	FiO_2	Pressure Condition	Pressure-Altitude Interaction	STATISTICALLY SIGNIFICANT COMPARISONS (P < .05) 30/0 vs.	30/30 vs.	60/60 vs.
$\dot{Q}$ ($\dot{V}_A/\dot{Q} = 0$)	.023	NS	NS	.023			
$\dot{Q}$ ($\dot{V}_A/\dot{Q}$ 0-.01)	.028	NS	NS	NS			
$\dot{Q}$ ($\dot{V}_A/\dot{Q}$ .01-.1)	.037	NS	NS	NS			
$\dot{Q}$ ($\dot{V}_A/\dot{Q}$ .1-1)	.029	.029	.0001	NS	0/0	0/0	0/0
$\dot{Q}$ ($\dot{V}_A/\dot{Q}$ 1-10)	.0002	.032	.0001	NS	0/0	0/0	0/0
$\dot{Q}$ ($\dot{V}_A/\dot{Q}$ 10-100)	.003	NS	.020	.004			
$\dot{V}$ ($\dot{V}_A/\dot{Q}$ 0-.01)	NS	NS	NS	NS			
$\dot{V}$ ($\dot{V}_A/\dot{Q}$ .01-.1)	NS	NS	NS	NS			
$\dot{V}$ ($\dot{V}_A/\dot{Q}$ .1-1)	NS	.01	.0001	.019	0/0	0/0	0/0
$\dot{V}$ ($\dot{V}_A/\dot{Q}$ 1-10)	.002	NS	.0001	NS	0/0	0/0	0/0
$\dot{V}$ ($\dot{V}_A/\dot{Q}$ 10-100)	.0007	NS	.012	.012			0/0
$\dot{V}$ ($\dot{V}_A/\dot{Q} = \infty$)	.025	NS	NS	NS			
$\log SD_{\dot{Q}}$	NS	NS	.0001	NS	0/0		0/0
$\log SD_{\dot{V}}$	NS	NS	NS	NS			
$DISP_R$	NS	NS	.030	NS			
$DISP_E$	NS	NS	NS	NS			
$DISP_{R-E}$	NS	NS	NS	NS			

Probability values calculated using 3-way ANOVA. Individual comparisons performed using Tukey-Kramer test.

Table 7: Experiment Duration

Altitude:	Ground	Ground	24,900 ft	Ground	Ground	Ground	Ground	24,900 ft
Breathing gas:	Air	100% oxygen	100% oxygen	Air	Air	Air	100% oxygen	100% oxygen
Mask Pressure:	0 mmHg	0 mmHg	0 mmHg	30 mmHg	30 mmHg	60 mmHg	60 mmHg	60 mmHg
Counterpressure:	0 mmHg	0 mmHg	0 mmHg	30 mmHg	0 mmHg	60 mmHg	60 mmHg	60 mmHg

Subject	Duration at Pressure min	Duration at Pressure min	Duration at Pressure min	Duration at Pressure min	Duration at Pressure min	Duration at Pressure min	Duration at Pressure min	Duration at Pressure min
RT*	11.7	14.0	11.8	11.0	9.8	6.7	6.0	8.0
KK*	10.8	12.1	**	9.4	10.8	7.2	3.3	**
FC	16.9	11.6	14.3	10.4	10.8	3.9	***	3.3
VW	14.7	11.8	14.7	6.5	6.4	1.8§	**	**
WS	14.5	12.8	14.8	8.3	6.1	4.3	4.6	5.0
TH	10.1	13.3	13.4	6.0	5.5	3.0	***	4.9†
JL	12.2	11.6	11.0	8.3	8.5	3.8	5.3	4.7†
TLH	11.8	12.5	12.6	7.1	8.2	3.7	4.4	4.0
SA	11.9	10.6	11.6	8.8	8.2	5.1	5.9	5.6§
TP	15.6	12.5	**	6.5	6.2	3.9	3.2	2.2
MEAN	13.0	12.3	13.0	8.2	8.1	4.6	4.7	4.5
STD DEV	2.2	1.0	1.5	1.7	2.0	1.4	1.1	2.2

* These subjects had a 2 minute warmup at 30 mmHg before increasing to 60 mmHg.

** Study aborted due to subject discomfort : Abdominal distress during ascent (KK); Failure to withstand pressure breathing (VW); Wrist discomfort (TP).

*** Technical Difficulties.

The durations at 60 mmHg mask pressure were all shorter than at 30 mmHg because of reduced subject tolerance. In two instances there was impaired consciousness (†): JL because of hypotension and TH because of severe hypocapnea (PCO_2 = 13.6 mmHg) and tetany. We therefore attempted to complete the measurements as quickly as possible during these runs, and often reduced the number of blood samples or the time over which they were drawn. Other subjects stopped because of tachypnea (§). Although at the end of each run some subjects indicated that they could have continued longer, all subjects exhibited evidence of labored breathing or exhaustion during the 60 mmHg exposures.

Of 25 experimental runs begun at 60 mmHg mouthpiece pressure, 11 lasted 4 minutes or less, and two runs terminated at 4.7 and 4.9 minutes with loss of consciousness. Both episodes were at altitude (see Table 4). In one individual (JL) this coincided with a mean arterial pressure of 60 mmHg, loss of pulse pressure and bradycardia, suggestive of lack of brain perfusion. The other episode (TH) was accompanied by tetany, (hypocapnea arterial PCO_2 = 13.6 mmHg) and (respiratory alkalosis arterial pH = 7.74; $[H^+]$ = 18.2 nM). Two runs (subjects SA at altitude with PPB - Fig. 27 and VW at ground level with 60 mmHg PPB) were terminated with marked tachypnea, consistent with respiratory muscle fatigue.

This study was not specifically designed to monitor maximum duration of PPB. It is possible that some individuals had difficulty completing the study because of inadequate motivation, a factor that could be overcome by training or, in actual combat, the knowledge of imminent death due to hypoxia. However, at least two foreshortened studies were due to physiological factors unlikely to be amenable to voluntary modification. All subjects felt that they were certainly close to their duration limits during 60 mmHg runs.

DISCUSSION

Gas exchange. Increasing mask pressure resulted in increase in $\dot{V}_A/\dot{Q}$ mismatching and a shift to lung units with higher $\dot{V}_A/\dot{Q}$. This partly confirmed the initial hypothesis and provided some explanation for the hyperventilation seen during positive pressure breathing. However, the hyperventilation observed was greater than required to maintain normocapnea. All subjects became hypocapneic, and one subject decreased his PCO_2 to 13.6 mmHg. The origin of this hyperventilation is not elucidated by this study. Our subjects were well-trained and it is unlikely that this represents anxiety. Subjects were unable to limit this hyperventilation even though they were all repeatedly instructed not to hyperventilate. It should be noted that because of the shift to high $\dot{V}_A/\dot{Q}$ ratios end-tidal PCO_2 would under-represent the arterial value. Future studies of gas exchange should therefore continue to include direct measurement of arterial gas values.

Ventilation to high $\dot{V}_A/\dot{Q}$ units tended to increase at altitude. Presumably this was an effect of the lower gas density at altitude, resulting in an alteration of breathing pattern compared to ground level.

After 45-90 minutes of 100% O_2 breathing, there was a tendency toward an increase in low $\dot{V}_A/\dot{Q}$ units and shunt, presumably due to microatelectasis. There was a reduction in perfusion to these units during PPB, although this did not reach statistical significance. Although it is highly likely that PPB would minimize or reverse such changes, an experiment to prove this assertion would require longer duration of O_2 breathing.

Hemodynamics. The expected impairment of cardiac function was observed in these experiments, and limited PPB duration in at least one subject.

Limiting factors to the use of the COMBAT EDGE. Using the COMBAT EDGE in this configuration, it is evident that subjects reach the limit of endurance within a few minutes. In addition to motivation, limiting factors include reduced cardiac output and cerebral blood flow, respiratory fatigue, pharyngeal muscle hypoperfusion and/or fatigue, hyperventilation and the possibility of pulmonary barotrauma (pnemothorax, mediastinal emphysema and arterial gas embolism).

There was significant inter-individual variability in tolerance of PPB. One of the major mechanisms of this intolerance is undoubtedly the reduction in cardiac output (most dramatically observed in subject JL - see Fig. 25. This is presumably due to the reduced venous return caused by increased intrathoracic pressure, and possibly also the increased pulmonary vascular resistance associated with an elevated alveolar pressure. Fig. 26 demonstrates that the transient augmentation of venous return by increasing G-suit pressure to 4:1. G-suit to mask ratio tends to normalize blood pressure. Perhaps some individuals are able to maintain a higher venous tone, either intrinsically or by active contraction of skeletal muscle.

It is noteworthy that mask leaks often resulted in transient increases in blood pressure. Such random leaks might be the reason that PPB using the COMBAT EDGE appears to be better tolerated in actual use (Travis & Morgan, 1994) than in these laboratory experiments, in which every effort was made to maintain a good mask seal. Redesign of the system to provide a phasic pressure response might produce more reproducible, and safer, conditions for the pilot.

A 1:1 G-suit-to-mask pressure ratio was used in these studies as requested. 3:1 and 4:1 ratios improved subject performance and have unknown effects on gas exchange.

SUMMARY OF RESULTS

1. There was an almost five-fold increase in minute ventilation at 60 mmHg mask pressure. The increase in minute ventilation was achieved by an increase in tidal volume but not of ventilatory frequency. The highest mask pressures resulted in a slight reduction in cardiac output.

2. PPB resulted in a shift of ventilation and perfusion to lung units at higher $\dot{V}_A/\dot{Q}s$. At the extremes of the distribution (including dead space) these changes were relatively insignificant. The changes in ventilation/perfusion of the lung did not explain the extreme hyperpnea observed during PPB. The increase in ventilation of high $\dot{V}_A/\dot{Q}$ units would tend to increase the discrepancy between end-tidal and arterial PO_2. Therefore, assessment of arterial PCO_2 during high levels of PPB should ideally be obtained by direct measurement of arterial gas tensions.

3. The data support the notion that PPB reduces shunt and perfusion to low $\dot{V}_A/\dot{Q}$ lung units, though it appears that the periods of high oxygen breathing used in this study were not sufficiently long to result in significant increases in these variables, and hence the result did not reach statistical significance.

4. While oxygen breathing resulted in a minor effect on some variables, there was a statistically significant effect of altitude exposure on several parameters. At 24,900 feet altitude heart rate was higher than at ground level. Arterial blood pressure was lower during PPB at altitude than at ground level. In addition, the respiratory effects on hemodynamics were less at altitude than at ground level, presumably because of lower gas density. The ability of the COMBAT EDGE regulator to maintain constant mask pressure was greater at altitude than at ground level. Minute ventilation tended to be higher at altitude than at ground level when mask pressure was elevated, though this did not reach statistical significance. Nevertheless, physiological testing of this apparatus at ground level is unlikely to predict fully its physiological effects under conditions of actual use.

5. Phasic swings in mask pressure seem to augment venous return and sustain mean arterial pressures in some people breathing with PPB at 1:1 G-suit-to-mask ratios. Increased G-suit pressures may augment blood return and maintain arterial pressures but have unknown effects on overall pulmonary gas exchange.

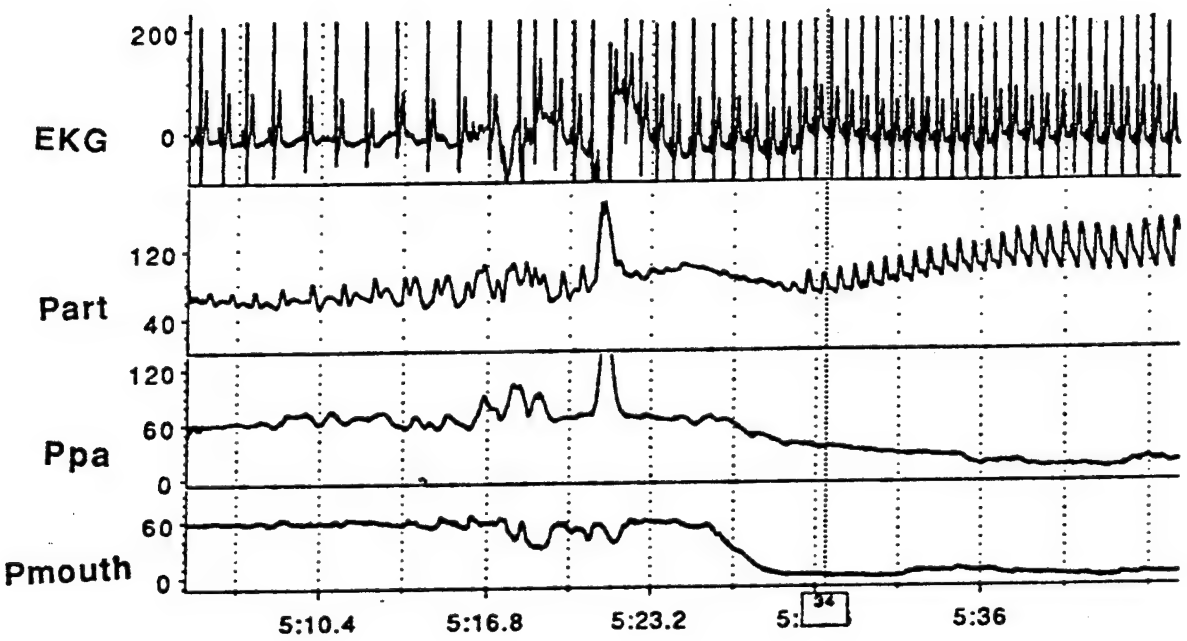


Figure 25. Loss Of Consciousness.

Example of an individual losing consciousness during 60 mmHg pressure run (JL at 24,900 ft altitude). At termination of run Part, Pmouth and Ppa all reached 60 mmHg.

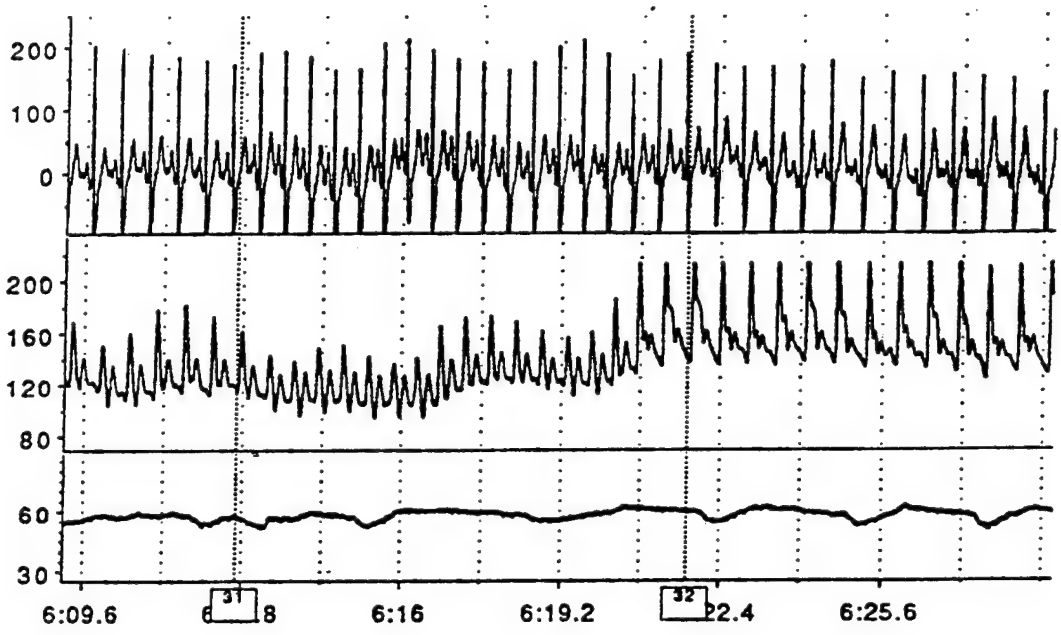


Figure 26. Increased G-Suit Pressure.

Effect on arterial pressure of inflating G-suit from 60 mmHg to 240 mmHg during 60 mmHg mask pressure PPB.

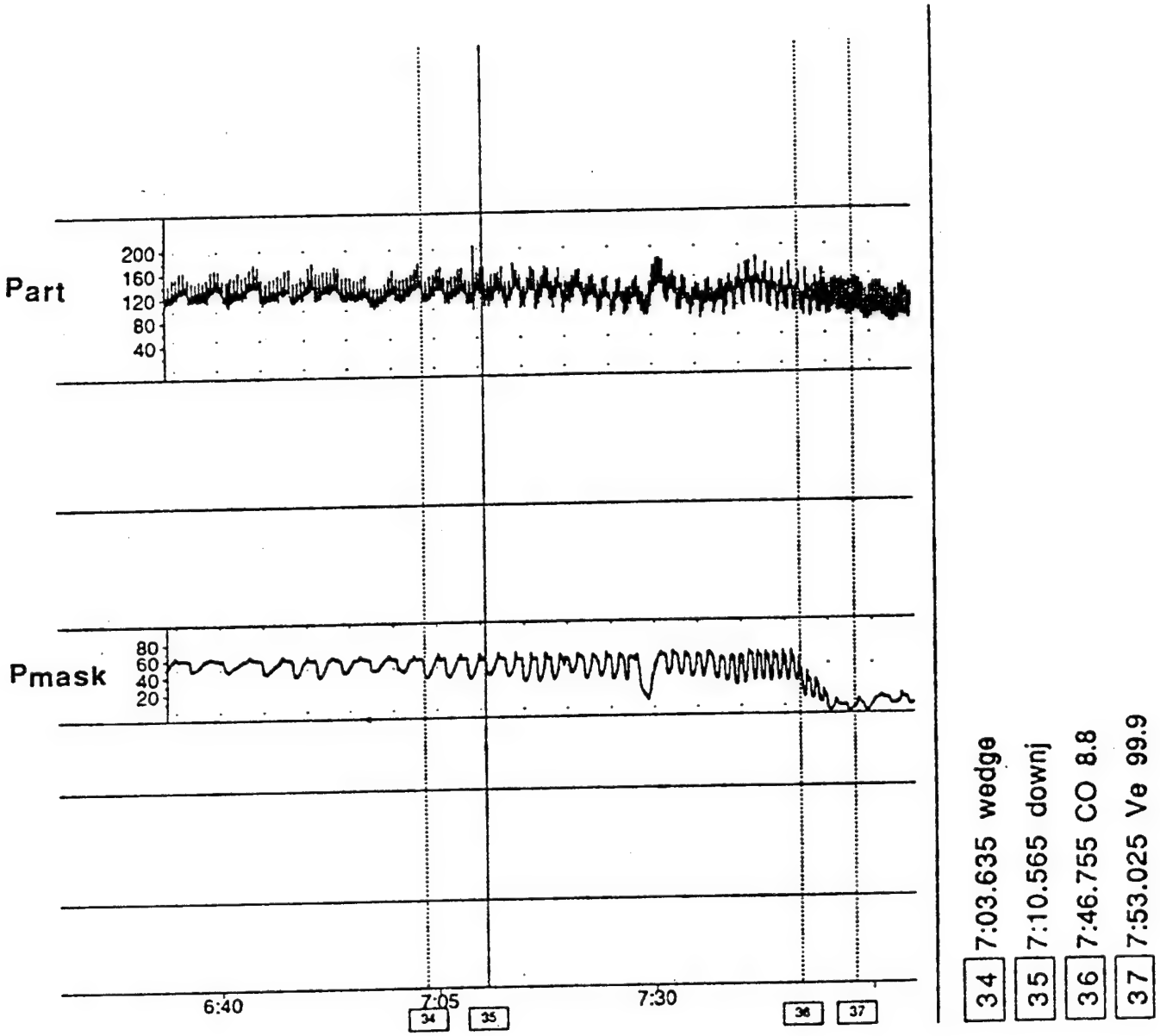


Figure 27. Tachypnea (Possible Respiratory Muscle Fatigue).

Example of tachypnea at termination of 60 mmHg pressure run. (SA at 24,900 ft altitude).

REFERENCES

Ackles KN, Porlier JAG, Holness DE, Wright GR, Lambert JM, McArthur WJ. Protection against the physiological effects of positive pressure breathing. Aviat Space Environ Med 49:753-758, 1978.

Balldin UI, Wranne B. Hemodynamic effects of extreme positive pressure breathing using a two-pressure flying suit. Aviat Space Environ Med 51:851-855, 1980.

Burns JW, Balldin UI. Assisted positive pressure breathing for augmentation of acceleration tolerance time. Aviat Space Environ Med 59:225-233, 1988.

Ernsting J. Some Effects of Raised Intrapulmonary Pressure. W.J MacKay Co. London, 1977.

Evans JW, Wagner PD. Limits on $\dot{V}_A/\dot{Q}$ distributions from analysis of experimental inert gas elimination. J Appl Physiol 42:889-898, 1977.

Fenn WO, Otis AB, Rahn H, Chadwick LE, Hegnauer AH. Displacement of blood from the lungs by pressure breathing. Am J Physiol 151:258-269, 1947.

Gagge AP, Allen SC, Marbarger JP. Pressure breathing. J Aviat Med 16:2-8, 1945.

Gale GE, Torre-Bueno JR, Moon RE, Saltzman HA, Wagner PD. Ventilation-perfusion inequality in normal humans during exercise at sea level and simulated altitude. J Appl Physiol 58:978-988, 1985

Goodman LS, Fraser WD, Eastman DE, Sharp GR, Ernsting J. Prevention of hypoxia. pp. 60-71. In Aviation Medicine, 2nd ed., 1988, Butterworth, London.

Goodman LS, Fraser WD, Eastman DE, Ackles KN. Cardiovascular responses to positive pressure breathing using the tactical life support system. Aviat Space Environ Med 63:662-669, 1992.

Goodman LS, Fraser WD, Ackles KN, Mohn D, Pecaric M. The effect of extending G-suit coverage on cardiovascular responses to positive pressure breathing. Aviat Space Environ Med 64:1101-1107, 1993.

Travis TW, Morgan TR. US Air Force positive-pressure breathing anti-G system (PPG): Subjective health effects and acceptance by pilots. Aviat Space Environ Med 65(Suppl 5):A75-A79, 1994.

Wagner PD. Pulmonary gas exchange: introduction. In: Muscular Exercise and the lung JA Dempsey and CE Reed (eds). Madison WI: Univ of Wisconsin Press, 1977, p. 315-323.

Wagner PD, Saltzman HA & West JB. Measurement of continuous distributions of ventilation-perfusion ratios: theory. J Appl Physiol 36:588-599, 1974.

APPENDIX

Summary of Blood Gases and Ventilation

Ground Level
Mean PB: 756 mmHg
Breathing gas: Air
Mask Pressure: 0 mmHg
Counterpressure: 0 mmHg
G-suit pressure 0 mmHg

Subject	PvO2	PvCO2	pHv	PaO2	PaCO2	pHa	VO2	VCO2	SaO2	SvO2	VE	Vf	Vt	VD/VT*	VD/VT*	VD**	VD**
	mmHg	mmHg		mmHg	mmHg		ml/m	ml/m			l/m BTPS	br/m	l BTPS	(ambient)	(mask)	l (ambient)	l (mask)
RT	44	42.5	7.34	87	41.3	7.36	263	168	0.97	0.80	6.4	12.1	0.531	0.447	0.447	0.237	0.237
KK	37	39.1	7.40	109	34.4	7.43	270	220	0.99	0.72	8.1	9.1	0.886	0.305	0.305	0.270	0.270
FC	42	37.1	7.39	107	34.2	7.41	307	242	0.99	0.79	8.1	10.3	0.785	0.230	0.230	0.181	0.181
VW	42	36.8	7.39	98	36.2	7.42	209	158	0.99	0.80	6.4	11.9	0.541	0.394	0.394	0.213	0.213
WS	43	45.9	7.35	94	41.9	7.37	214	168	0.98	0.76	6.3	13.7	0.457	0.432	0.432	0.197	0.197
TH	45	41.7	7.39	108	36.5	7.40	250	215	0.99	0.83	7.8	10.5	0.742	0.336	0.336	0.249	0.249
JL	43	42.5	7.36	97	38.4	7.38	239	196	0.98	0.81	5.8	7.7	0.748	0.229	0.229	0.171	0.171
TLH	45	42.1	7.37	105	39.2	7.39	257	198	0.98	0.82	7.2	15.6	0.462	0.380	0.380	0.175	0.175
SA	41	41.3	7.37	99	38.3	7.39	328	252	0.99	0.78	7.7	10.9	0.706	0.249	0.249	0.176	0.176
TP	43	43.2	7.35	110	38.0	7.38	200	171	0.99	0.78	7.3	20.0	0.365	0.456	0.456	0.166	0.166
MEAN	43	41.2	7.37	101	37.8	7.39	254	199	0.98	0.79	7.1	12.2	0.622	0.346	0.346	0.204	0.204
STD DEV	2	2.8	0.02	8	2.6	0.02	41	33	0.01	0.03	0.8	3.5	0.172	0.089	0.089	0.037	0.037

VD/DT, calculated using the Enghoff modification of the Bohr equation.
*VD/VT has been calculated using two different values for Pb: ambient (chamber) pressure and mask pressure.
**Both volumes are reported in liters BTPS, using ambient (chamber) pressure.

Summary of Blood Gases and Ventilation (cont'd)

Ground Level
Mean PB: 756 mmHg
Breathing gas: Air
Mask Pressure: 30 mmHg
Counterpressure: 30 mmHg
G-suit pressure 30 mmHg

Subject	PvO2	PvCO2	pHv	PaO2	PaCO2	pHa	VO2	VCO2	SaO2	SvO2	VE	Vf	Vt	VD/VT*	VD/VT*	VD**	VD**
	mmHg	mmHg		mmHg	mmHg		ml/m	ml/m			l/m BTPS	br/m	l BTPS	(ambient)	(mask)	l (ambient)	l (mask)
RT	35	30.5	7.42	129	27.3	7.49	267	272	0.99	0.74	16.4	8.3	1.972	0.461	0.438	0.909	0.864
KK	31	32.0	7.44	134	27.3	7.52	350	380	0.99	0.67	24.7	20.2	1.222	0.488	0.466	0.596	0.569
RC	35	34.5	7.46	127	25.8	7.53	268	337	1.00	0.71	17.3	5.5	3.151	0.329	0.301	1.037	0.948
VW	37	30.4	7.51	146	21.3	7.61	379	586	1.00	0.78	45.4	30.4	1.493	0.450	0.426	0.671	0.636
WS	36	28.4	7.51	144	20.5	7.63	297	474	1.00	0.74	32.8	13.7	2.391	0.363	0.335	0.867	0.801
TH	33	26.2	7.57	150	17.4	7.68	318	582	1.00	0.78	44.8	14.8	3.028	0.331	0.303	1.001	0.918
JL	36	37.4	7.41	118	31.4	7.46	221	260	0.99	0.74	13.8	8.4	1.637	0.467	0.444	0.764	0.727
TLH	38	28.4	7.51	149	22.3	7.59	277	427	1.00	0.81	25.2	9.7	2.595	0.318	0.289	0.825	0.750
SA	34	32.6	7.46	124	27.8	7.51	318	371	0.99	0.73	18.3	6.7	2.725	0.355	0.327	0.966	0.891
TP	36	30.5	7.50	131	24.3	7.57	153	315	0.99	0.76	18.9	12.4	1.521	0.386	0.360	0.587	0.548
MEAN	35	31.1	7.48	135	24.5	7.56	285	400	1.00	0.75	25.7	13.0	2.174	0.395	0.369	0.822	0.920
STD DEV	2	3.2	0.05	11	4.2	0.07	65	117	0.00	0.04	11.6	7.5	0.694	0.065	0.068	0.164	0.144

VD/DT, calculated using the Enghoff modification of the Bohr equation.
*VD/VT has been calculated using two different values for Pb: ambient (chamber) pressure and mask pressure.
**Both volumes are reported in liters BTPS, using ambient (chamber) pressure.

Summary of Blood Gases and Ventilation (cont'd)

Ground Level
Mean PB: 756 mmHg
Breathing gas: Air
Mask Pressure: 30 mmHg
Counterpressure: 0 mmHg
G-suit pressure 0 mmHg

Subject	PvO2	PvCO2	pHv	PaO2	PaCO2	pHa	VO2	VCO2	SaO2	SvO2	VE	Vf	Vt	VD/VT*	VD/VT*	VD**	VD**
	mmHg	mmHg		mmHg	mmHg		ml/m	ml/m			l/m BTPS	br/m	l BTPS	(ambient)	(mask)	l (ambient)	l (mask)
RT	31	27.8	7.47	127	24.9	7.53	311	329	0.99	0.70	20.3	9.1	2.227	0.423	0.399	0.942	0.889
KK	30	33.6	7.48	134	24.5	7.55	280	340	1.00	0.65	23.2	16.9	1.373	0.456	0.433	0.626	0.594
FC	33	29.3	7.46	135	24.0	7.55	299	383	1.00	0.70	21.4	6.2	3.445	0.335	0.307	1.152	1.058
VW	45	27.0	7.54	145	18.6	7.67	291	771	1.00	0.89	58.9	23.1	2.550	0.362	0.335	0.923	0.854
WS	34	27.1	7.56	147	17.5	7.68	292	666	1.00	0.75	50.5	15.8	3.194	0.316	0.287	1.011	0.917
TH	31	26.8	7.57	149	17.4	7.68	285	568	1.00	0.74	49.8	18.8	2.648	0.410	0.385	1.086	1.019
JL	33	35.8	7.43	127	26.9	7.51	236	311	0.99	0.70	17.9	8.1	2.211	0.427	0.403	0.945	0.891
TLH	39	32.1	7.47	129	28.4	7.51	274	370	1.00	0.80	20.0	11.1	1.799	0.415	0.390	0.747	0.702
SA	32	30.8	7.48	130	23.6	7.56	293	403	1.00	0.70	22.6	7.7	2.939	0.332	0.304	0.977	0.893
TP	36	31.0	7.49	146	18.9	7.61	278	569	1.00	0.77	37.7	15.8	2.385	0.285	0.254	0.680	0.606
MEAN	34	30.1	7.49	137	22.5	7.58	284	471	1.00	0.74	32.2	13.3	2.477	0.376	0.350	0.909	0.930
STD DEV	5	3.1	0.05	9	4.0	0.07	20	161	0.00	0.07	15.5	5.6	0.625	0.057	0.060	0.172	0.159

VD/DT, calculated using the Enghoff modification of the Bohr equation.
*VD/VT has been calculated using two different values for Pb: ambient (chamber) pressure and mask pressure.
**Both volumes are reported in liters BTPS, using ambient (chamber) pressure.

Summary of Blood Gases and Ventilation (cont'd)

Ground Level
Mean PB: 756 mmHg
Breathing gas: Air
Mask Pressure: 60 mmHg
Counterpressure: 60 mmHg
G-suit pressure 60 mmHg

Subject	PvO2	PvCO2	pHv	PaO2	PaCO2	pHa	VO2	VCO2	SaO2	SvO2	VE	Vf	Vt	VD/VT*	VD/VT*	VD**	VD**
	mmHg	mmHg		mmHg	mmHg		ml/m	ml/m			l/m BTPS	br/m	l BTPS	(ambient)	(mask)	l (ambient)	l (mask)
RT	27	32.2	7.47	134	23.3	7.55	306	333	1.00	0.60	23.1	9.8	2.352	0.446	0.400	1.050	0.941
KK	28	37.9	7.42	119	30.9	7.47	340	280	1.00	0.55	21.9	30.9	0.707	0.629	0.598	0.445	0.423
FC	33	17.5	7.46	138	21.9	7.57	350	451	1.00	0.71	23.0	8.1	2.838	0.209	0.143	0.592	0.406
VW	30	24.1	7.58	156	18.1	7.66	480	803	1.00	0.70		47.4		0.402	0.351		
WS	37	30.0	7.48	143	20.2	7.64	180	534	1.00	0.77	40.8	20.5	1.992	0.412	0.362	0.821	0.721
TH	31	27.3	7.56	152	15.6	7.71	338	722	1.00	0.73	62.6	20.4	3.069	0.336	0.280	1.030	0.859
JL	31	35.7	7.43	135	26.1	7.52	169	270	0.99	0.65	16.2	9.4	1.721	0.432	0.384	0.744	0.661
TLH	36	31.2	7.48	148	22.4	7.58	204	608	1.00	0.77	35.9	10.4	3.456	0.323	0.266	1.115	0.919
SA				132	20.3	7.62	288	473	1.00		32.6	10.9	2.987	0.362	0.308	1.082	0.920
TP	33	32.1	7.48	146	21.4	7.61	232	377	1.00	0.72	23.7	13.8	1.714	0.334	0.277	0.573	0.475
MEAN	32	29.8	7.48	140	22.0	7.59	289	485	1.00	0.69	31.1	16.2	2.315	0.389	0.337	0.828	0.849
STD DEV	3	6.2	0.05	11	4.2	0.07	96	182	0.00	0.07	14.2	12.5	0.866	0.109	0.118	0.253	0.222

VD/DT, calculated using the Enghoff modification of the Bohr equation.
*VD/VT has been calculated using two different values for Pb: ambient (chamber) pressure and mask pressure.
**Both volumes are reported in liters BTPS, using ambient (chamber) pressure.

Summary of Blood Gases and Ventilation (cont'd)

Ground Level
Mean PB: 756 mmHg
Breathing gas: 100% oxygen
Mask Pressure: 0 mmHg
Counterpressure: 0 mmHg
G-suit pressure 0 mmHg

Subject	PvO2	PvCO2	pHv	PaO2	PaCO2	pHa	VO2†	VCO2	SaO2	SvO2	VE	Vf	Vt	VD/VT*	VD/VT*	VD**	VD**
	mmHg	mmHg		mmHg	mmHg		ml/m	ml/m			l/m BTPS	br/m	l BTPS	(ambient)	(mask)	l (ambient)	l (mask)
RT	63	44.7	7.34	587	37.6	7.37		200	1.00	0.93	7.8	15.1	0.517	0.409	0.409	0.211	0.211
KK	46	42.3	7.37	574	35.8	7.42		212	1.00	0.83	8.7	14.4	0.603	0.411	0.411	0.248	0.248
RC	54	38.0	7.41	626	33.7	7.45		255	1.00	0.89	8.7	5.9	1.480	0.250	0.250	0.370	0.370
VW	55	40.8	7.40	563	35.3	7.43		229	1.00	0.90	9.3	16.0	0.583	0.398	0.398	0.232	0.232
WS	53	42.6	7.37	585	38.3	7.40		178	1.00	0.87	7.4	15.4	0.479	0.455	0.455	0.218	0.218
TH	65	41.3	7.39	573	34.0	7.43		179	1.00	0.95	6.6	10.5	0.632	0.315	0.315	0.199	0.199
JL	55	41.9	7.36	579	37.1	7.39		204	1.00	0.90	6.2	8.3	0.747	0.235	0.235	0.175	0.175
TLH	61	41.7	7.37	590	36.5	7.42		220	1.00	0.93	7.9	15.6	0.506	0.342	0.342	0.173	0.173
SA	49	37.7	7.39	560	34.0	7.43		238	1.00	0.88	8.4	11.1	0.759	0.279	0.279	0.212	0.212
TP	54	42.0	7.36	555	35.8	7.41		196	1.00	0.88	8.0	14.8	0.543	0.410	0.410	0.222	0.222
MEAN	56	41.3	7.38	579	35.8	7.41		211	1.00	0.90	7.9	12.7	0.685	0.350	0.350	0.226	0.226
STD DEV	6	2.1	0.02	20	1.6	0.02		25	0.00	0.04	1.0	3.5	0.295	0.077	0.077	0.056	0.056

VD/DT, calculated using the Enghoff modification of the Bohr equation.
*VD/VT has been calculated using two different values for Pb: ambient (chamber) pressure and mask pressure.
**Both volumes are reported in liters BTPS, using ambient (chamber) pressure.
†VO2 could not be calculated during 100% O2 breathing because of the open circuit technique used in this experiment.

Summary of Blood Gases and Ventilation (cont'd)

Ground Level
Mean PB: 756 mmHg
Breathing gas: 100% oxygen
Mask Pressure: 60 mmHg
Counterpressure: 60 mmHg
G-suit pressure 60 mmHg

Subject	PvO2	PvCO2	pHv	PaO2	PaCO2	pHa	VO2†	5	SaO2	SvO2	VE	Vf	Vt	VD/VT*	VD/VT*	VD**	VD**
	mmHg	mmHg		mmHg	mmHg		ml/m	ml/m			l/m BTPS	br/m	l BTPS	(ambient)	(mask)	l (ambient)	l (mask)
RT	34	35.2	7.44	664	24.1	7.55		285	1.00	0.72	18.7	12.5	1.495	0.453	0.407	0.678	0.609
KK	36	34.2	7.44	620	27.1	7.53		402	1.00	0.74	32.6	35.7	0.913	0.607	0.574	0.554	0.524
FC																	
VW																	
WS	36	28.5	7.52	585	16.7	7.69		615	1.00	0.76	44.7	21.4	2.087	0.362	0.308	0.756	0.643
TH																	
JL	37	35.1	7.42	630	26.2	7.52		279	1.00	0.74	16.9	10.5	1.612	0.461	0.415	0.743	0.669
TLH	41	29.5	7.49	696	21.7	7.60		456	1.00	0.85	27.0	12.0	2.248	0.327	0.271	0.736	0.609
SA	32	27.0	7.52	603	19.1	7.63		396	1.00	0.74	30.5	10.1	3.017	0.411	0.361	1.240	1.089
TP	41	32.1	7.48	590	20.6	7.62		359	1.00	0.82	21.8	13.5	1.618	0.308	0.248	0.499	0.401
MEAN	37	31.7	7.47	627	22.2	7.59		399	1.00	0.77	27.5	16.5	1.856	0.418	0.369	0.744	0.872
STD DEV	3	3.4	0.04	41	3.8	0.06		115	0.00	0.05	9.6	9.3	0.670	0.102	0.111	0.240	0.214

VD/DT, calculated using the Enghoff modification of the Bohr equation.
*VD/VT has been calculated using two different values for Pb: ambient (chamber) pressure and mask pressure.
**Both volumes are reported in liters BTPS, using ambient (chamber) pressure.
†VO2 could not be calculated during 100% O2 breathing because of the open circuit technique used in this experiment.

Summary of Blood Gases and Ventilation (cont'd)

24,900 ft
Mean PB: 283 mmHg
Breathing gas: 100% oxygen
Mask Pressure: 0 mmHg
Counterpressure: 0 mmHg
G-suit pressure 0 mmHg

Subject	PvO2	PvCO2	pHv	PaO2	PaCO2	pHa	VO2†	VCO2	SaO2	SvO2	VE	Vf	Vt	VD/VT*	VD/VT*	VD**	VD**
	mmHg	mmHg		mmHg	mmHg		ml/m	ml/m			l/m BTPS	br/m	l BTPS	(ambient)	(mask)	l (ambient)	l (mask)
RT	43	41.0	7.35	168	38.7	7.37		192	0.99	0.79	8.3	16.9	0.489	0.478	0.478	0.234	0.234
KK																	
FC	47	38.7	7.41	181	36.7	7.43		224	1.00	0.80	9.0	8.2	1.101	0.418	0.418	0.461	0.461
VW	47	40.5	7.40	191	35.8	7.41		230	1.00	0.83	9.6	13.3	0.718	0.420	0.420	0.302	0.302
WS	42	39.8	7.39	182	35.7	7.41		188	1.00	0.77	7.7	14.5	0.534	0.407	0.407	0.217	0.217
TH	52	43.3	7.37	198	38.5	7.38		138	1.00	0.88	8.6	13.3	0.644	0.636	0.636	0.409	0.409
JL	47	41.2	7.36	182	28.7	7.37		153	1.00	0.84	6.1	10.6	0.576	0.242	0.242	0.140	0.140
TLH	48	40.7	7.37	193	37.7	7.39		165	1.00	0.85	7.1	16.9	0.421	0.467	0.467	0.197	0.197
SA	41	38.0	7.37	184	38.0	7.37		225	0.99	0.78	9.1	9.5	0.953	0.438	0.438	0.418	0.418
TP																	
MEAN	46	40.4	7.38	185	36.2	7.39		189	0.99	0.82	8.2	12.9	0.679	0.439	0.439	0.297	0.297
STD DEV	4	1.6	0.02	9	3.2	0.02		35	0.00	0.04	1.1	3.2	0.236	0.108	0.108	0.119	0.119

VD/DT, calculated using the Enghoff modification of the Bohr equation.
***VD/VT has been calculated using two different values for Pb: ambient (chamber) pressure and mask pressure.**
****Both volumes are reported in liters BTPS, using ambient (chamber) pressure.**
†VO2 could not be calculated during 100% O2 breathing because of the open circuit technique used in this experiment.

Summary of Blood Gases and Ventilation (cont'd)

24,900 ft
Mean PB: 283 mmHg
Breathing gas: 100% oxygen
Mask Pressure: 60 mmHg
Counterpressure: 60 mmHg
G-suit pressure 60 mmHg

Subject	PvO2	PvCO2	pHv	PaO2	PaCO2	pHa	VO2†	VCO2	SaO2	SvO2	VE	Vf	Vt	VD/VT*	VD/VT*	VD**	VD**
	mmHg	mmHg		mmHg	mmHg		ml/m	ml/m			l/m BTPS	br/m	l BTPS	(ambient)	(mask)	l (ambient)	l (mask)
RT	36	32.8	7.47	206	24.5	7.53		107	1.00	0.75	9.6	16.7	0.572	0.594	0.490	0.340	0.280
KK																	
RC	39	34.4	7.46	270	23.9	7.56		400	1.00	0.67	25.2	12.1	2.082	0.425	0.279	0.885	0.581
VW																	
WS	29	35.9	7.46	247	17.0	7.67		467	1.00	0.58		18.0		0.471	0.337		
TH	31	23.7	7.59	256	13.6	7.74		642	1.00	0.75	81.0	22.9	3.538	0.494	0.365	1.747	1.292
JL	28	34.3	7.44	238	23.6	7.55		291	1.00	0.60	22.3	10.0	2.234	0.525	0.405	1.174	0.905
TLH	35	30.7	7.48	255	19.9	7.62		470	1.00	0.76	31.6	13.3	2.374	0.349	0.184	0.830	0.437
SA	30	31.9	7.48	246	20.8	7.60		496	1.00	0.67	36.6	19.4	1.884	0.436	0.292	0.821	0.550
TP	31	31.2	7.47	244	14.8	7.70		638	1.00	0.67	68.3	28.8	2.373	0.457	0.319	1.085	0.757
MEAN	32	31.9	7.48	245	19.8	7.62		439	1.00	0.68	39.2	17.7	2.151	0.469	0.334	0.983	0.698
STD DEV	4	3.7	0.05	19	4.2	0.08		177	0.00	0.07	25.9	6.1	0.876	0.073	0.091	0.429	0.336

VD/DT, calculated using the Enghoff modification of the Bohr equation.
*VD/VT has been calculated using two different values for Pb: ambient (chamber) pressure and mask pressure.
**Both volumes are reported in liters BTPS, using ambient (chamber) pressure.
†VO2 could not be calculated during 100% O2 breathing because of the open circuit technique used in this experiment.

Cardiac Output, Heart Rate, CVP, Mean Arterial and PA Pressures

Ground Level
Mean PB: 756 mmHg
Breathing gas: Air
Mask Pressure: 0 mmHg
Counterpressure: 0 mmHg
G-suit pressure: 0 mmHg

Subject	Cardiac Output O2	Cardiac Output MG	Cardiac Output TD	HR Start	HR Mid	HR End	Part Start	Part Mid	Part End	Ppa Start	Ppa Mid	Ppa End	CVP Start	CVP Mid	CVP End
	l/m	l/m	l/m												
RT	7.3	5.1		•	56	58	•	77	74	•	0.0	-2.0	•	-4.1	-4.2
KK	6.4	4.5	5.0	66	65	60	96	94	93	9.7	•	10.2	2.2	3.0	2.4
FC	8.5	8.0	6.6	65	64	•	•	90	89	•	8.6	7.2	•	0.2	-0.4
VW	5.8	5.1	7.1	82	78	75	107	100	95	4.2	7.8	•	-4.6	-1.7	-1.8
WS	5.7	5.8	5.3	59	63	64	98	104	97	6.2	•	7.5	-2.4	-2.0	-2.8
TH	8.7	7.3	6.3	85	80	90	74	76	74	4.0	8.0	4.5	-4.2	-5.0	-5.5
JL	7.7	7.2	5.7	86	75	76	90	87	90	0.5	4.0	1.9	•	-7.4	-7.3
TLH	7.9	8.2	6.5	87	81	79	105	100	96	12.1	12.2	10.2	2.6	1.8	1.9
SA	9.4	9.0	8.4	77	90	79	99	102	94	11.0	13.4	10.5	3.6	2.8	3.9
TP	4.9	4.4	4.7	74	65	67	85	87	88	7.1	8.7	6.6	-3.5	-3.4	-3.7
MEAN	7.22	6.48	6.16	75.67	71.70	72.00	94.25	91.70	89.00	6.85	7.84	6.29	-0.90	-1.58	-1.75
STD DEV	1.47	1.69	1.16	10.32	10.60	10.46	10.90	10.06	8.45	3.94	4.27	4.21	3.55	3.50	3.65

O2 Fick, calculated using the Fick principle from oxygen consumption and the a-v oxygen content difference; MIG Fick, calculated using the Fick principle from the four least soluble inert gases; TD, determined by thermodilution.

Cardiac Output, Heart Rate, CVP, Mean Arterial and PA Pressures

Ground Level
Mean PB: 756 mmHg
Breathing gas: Air
Mask Pressure: 30 mmHg
Counterpressure: 30 mmHg
G-suit pressure: 30 mmHg

Subject	Cardiac Output			HR Start	HR Mid	HR End	Part Start	Part Mid	Part End	Ppa Start	Ppa Mid	Ppa End	CVP Start	CVP Mid	CVP End
	O2	MIG	TD												
	l/m	l/m	l/m												
RT	5.2	3.7		73	75	72	87	87	95	18.9	18.7	14.7	19.1	18.8	18.1
KK	7.0	4.3	4.1	66	73	78	122	129	129	35.1	35.2	37.7	34.9	37.7	37.2
FC	4.9	4.9	5.7	84	82	95	112	102	113	35	34.5	37.2	23.5	22.5	24.8
VW	8.9	8.1	6.9	98	119	112	115	125	125	31.6	34.6	29.5	21.1	23.7	23.1
WS	6.6	5.9	6.0	92	104	102	81	108	107	28.3	30.1	28.9	21	26.2	22.2
TH	7.1	8.1	6.8	111	126	109	87	96	101	27.4	27.8	30.9	15.9	16.5	18.8
JL	4.7	4.8	5.6	100	99	91	123	123	121	32.3	35.5	33.4	•	•	28.2
TLH	7.1	7.3	5.6	112	116	113	119	126	123	35.2	39.3	35.4	25	24.1	23.7
SA	6.7	7.0	7.2	80	92	85	112	114	109	32	36	33.6	23.3	24	29.6
TP	3.5	4.8	4.8	82	94	87	103	99	98	31.7	38.3	23.8	23.8	23.2	23
MEAN	6.18	5.89	5.83	89.80	98.00	94.40	106.10	110.90	112.10	30.75	33.00	30.51	23.07	24.08	24.87
STD DEV	1.57	1.63	1.00	15.48	18.40	14.35	15.72	14.65	12.02	4.94	6.08	6.97	5.24	5.90	5.61

O2 Fick, calculated using the Fick principle from oxygen consumption and the a-v oxygen content difference; MIG Fick, calculated using the Fick principle from the four least soluble inert gases; TD, determined by thermodilution.

Cardiac Output, Heart Rate, CVP, Mean Arterial and PA Pressures

Ground Level
Mean PB: 756 mmHg
Breathing gas: Air
Mask Pressure: 30 mmHg
Counterpressure: 0 mmHg
G-suit pressure: 0 mmHg

Subject	Cardiac Output			HR Start	HR Mid	HR End	Part Start	Part Mid	Part End	Ppa Start	Ppa Mid	Ppa End	CVP Start	CVP Mid	CVP End
	O2	MIG	TD												
	l/m	l/m	l/m												
RT	4.8	5.0		71	81	92	94	94	83	25.3	25.9	28.7	18	19.2	21.8
KK	4.9	3.8	4.8	70	84	82	114	121	120	42.9	44.3	47.6	29.8	30.2	30.6
FC	5.5	3.9	8.6	89	91	86	107	107	108	30.8	31.2	28.9	30	29.8	30.4
VW	12.2	10.6	10.2	102	128	122	106	110	121	27.7	29.6	34.4	13.1	19.4	18.3
WS	6.8	7.3	6.0	80	114	105	92	98	99	28.6	32.1	24.3	16	16.1	16
TH	5.3	6.2	6.2	94	103	148	86	91	94	28.1	29.4	31.7	13.5	12.9	13.4
JL	4.2	4.0	2.7	112	106	108	111	110	111	32.5	35.2	34.3	•	28.4	27.8
TLH	7.0	7.2	6.4	117	109	111	116	115	102	32.8	31.1	31.4	21.7	14.9	12.7
SA	5.4	5.7	5.9	102	97	95	104	102	101	29.6	34.6	31.9	21.5	21.5	21.6
TP	5.8	5.3	5.3	96	103	104	94	98	97	28.1	30.2	31.9	15	15.5	16.3
MEAN	6.2	5.9	6.2	93.3	101.6	105.3	102.4	104.6	103.6	30.64	32.36	32.51	19.84	20.79	20.89
STD DEV	2.3	2.1	2.1	16.01	14.13	19.27	10.27	9.62	11.72	4.87	4.9601	6.07	6.48	6.49	6.74

O2 Fick, calculated using the Fick principle from oxygen consumption and the a-v oxygen content difference; MIG Fick, calculated using the Fick principle from the four least soluble inert gases; TD, determined by thermodilution.

Cardiac Output, Heart Rate, CVP, Mean Arterial and PA Pressures

Ground Level
Mean PB: 756 mmHg
Breathing gas: Air
Mask Pressure: 60 mmHg
Counterpressure: 60 mmHg
G-suit pressure: 60 mmHg

	Cardiac Output														
Subject	O2	MG	TD	HR Start	HR Mid	HR End	Part Start	Part Mid	Part End	Ppa Start	Ppa Mid	Ppa End	CVP Start	CVP Mid	CVP End
	l/m	l/m	l/m												
RT	3.7	4.1		78	88	105	112	114	104	50.4	70.4	51.9	44.4	49.2	45.8
KK	4.7	4.2	4.7	84	89	90	118	131	133	52.3	48.3	56.7	35.1	38.8	36.9
FC	6.3		5.3	112	96	112	133	147	146	59.1	64	77.8	56.2	56.4	55.4
VW	8.2		8.1	119	119	•	123	134	•	52.5	52.9	•	44.2	42.6	•
WS	4.6	6.0	7.2	110	109	113	86	101	109	54.5	46	50.8	45.2	34.3	44.3
TH	6.3	7.0		142	130	130	98	111	108	49.6	48.4	53.9	35.7	32.9	36.7
JL	2.8	3.6	3.3	106	123	109	135	129	106	60	62.3	60.6	•	57	•
TLH	4.4	7.0	8.0	131	171	140	136	138	138	60.9	61.6	52.5	51.8	47.3	35.2
SA	1.7	6.6	6.7	104	115	116	115	120	122	56.1	59.5	58.3	51.3	51.9	50.9
TP	4.2	3.6	4.1	94	129	131	117	114	116	56	51.5	57	47.2	44.7	45.8
MEAN	4.7	5.2	5.9	108	116.9	116.2	117.3	123.9	120.222	55.14	56.49	57.722	45.68	45.51	43.88
STD DEV	1.9	1.5	1.8	19.7709	24.5	15.28	16.08	14.19	15.43	3.98	8.16	8.19	7.05	8.48	7.22

O2 Fick, calculated using the Fick principle from oxygen consumption and the a-v oxygen content difference; MIG Fick, calculated using the Fick principle from the four least soluble inert gases; TD, determined by thermodilution.

Cardiac Output, Heart Rate, CVP, Mean Arterial and PA Pressures

Ground Level
Mean PB: 756 mmHg
Breathing gas: 100% oxygen
Mask Pressure: 0 mmHg
Counterpressure: 0 mmHg
G-suit pressure: 0 mmHg

	Cardiac Output														
Subject	O2	MIG	TD	HR Start	HR Mid	HR End	Part Start	Part Mid	Part End	Ppa Start	Ppa Mid	Ppa End	CVP Start	CVP Mid	CVP End
	l/m	l/m	l/m												
RT		8.9		71	63	63	83.4	78.7	81.6	7.5	•	•	0.9	1.3	1.2
KK		5.3	7.0	58	67	65	96.9	101.8	100.2	7.4	•	5.2	0.6	0.6	1
FC		6.7	7.1	72	64	65	87.6	89.1	85.8	6.9	•	•	-0.4	-0.7	-0.8
VW		6.6	6.2	69	77	68	96.2	96.8	97.8	•	6.7	6.7	-4.2	-4.9	•
WS		5.2	4.5	59	56	57	100.7	95.8	99.6	4.1	4.9	•	-3.8	-4.2	-5.2
TH		8.1	6.6	79	81	81	81.8	82.1	79.7	•	•	0.3	-3	-3.5	-3.5
JL		6.6	6.4	71	73	73	96.9	97	98.9	•	9.8	10.4	0.5	•	0.3
TLH		6.3	6.2	82	78	84	91.9	92	91.6	7.6	8.5	7.5	-3.5	-3.8	-3.5
SA		7.3	6.1	70	81	65	95	95.6	97.3	7.8	10.3	7.4	0.9	1.5	0.5
TP		4.1	4.6	70	71	77	85.7	85.4	83.8	4.6	6.7	5	-3.8	-3.7	-4.2
MEAN		6.5	6.1	70.1	71.1	69.8	91.61	91.43	91.63	6.56	7.82	6.07	-1.58	-1.9333	-1.58
STD DEV		1.4	0.9	7.43	8.45	8.64	6.55	7.42	8.15	1.54	2.08	3.11	2.24	2.58	2.50

O2 Fick, calculated using the Fick principle from oxygen consumption and the a-v oxygen content difference; MIG Fick, calculated using the Fick principle from the four least soluble inert gases; TD, determined by thermodilution.

Cardiac Output, Heart Rate, CVP, Mean Arterial and PA Pressures

Ground Level
Mean PB: 756 mmHg
Breathing gas: 100% oxygen
Mask Pressure: 60 mmHg
Counterpressure: 60 mmHg
G-suit pressure: 60 mmHg

Subject	Cardiac Output O2 l/m	Cardiac Output MG l/m	Cardiac Output TD l/m	HR Start	HR Mid	HR End	Part Start	Part Mid	Part End	Ppa Start	Ppa Mid	Ppa End	CVP Start	CVP Mid	CVP End
RT		2.9		77	81	80	110	127.1	126.1	44.9	49.4	47.2	37.6	42.2	44.5
KK		5.1	5.9	86	85	86	123.7	132.2	132.5	57.8	55.3	•	45.7	44.9	44.5
FC				•	•	•	•	•	•	•	•	•	•	•	•
VW				•	•	•	•	•	•	•	•	•	•	•	•
WS		5.4	6.5	100	113	96	89.1	120.7	124	54.3	•	•	41.8	39.2	44.3
TH				•	•	•	•	•	•	•	•	•	•	•	•
JL		2.9	3.8	113	120	127	141.1	141.9	142.9	61.7	65.8	65.3	•	59.9	•
TLH		6.1	7.4	109	126	127	139	138.1	138.2	58.5	57.6	58.1	42.3	35.2	34.4
SA		5.6	5.0	91	97	82	119.8	132.7	132.5	57.6	•	59.2	49.6	51.9	52.5
TP		4.3	4.3	101	122	117	117.2	117.1	118.4	57.6	40.2	56.9	48.4	43.9	46.2
MEAN		4.6	5.5	96.71	106.3	102.1	119.99	129.971	130.657	56.06	53.66	57.34	44.23	45.314	44.4
STD DEV		1.3	1.4	12.7895	18.47	21.02	17.71	8.95	8.45	5.37	9.55	6.53	4.52	8.24	5.81

O2 Fick, calculated using the Fick principle from oxygen consumption and the a-v oxygen content difference; MIG Fick, calculated using the Fick principle from the four least soluble inert gases; TD, determined by thermodilution.

Cardiac Output, Heart Rate, CVP, Mean Arterial and PA Pressures

24,900 ft
Mean PB: 283 mmHg
Breathing gas: 100% oxygen
Mask Pressure: 0 mmHg
Counterpressure: 0 mmHg
G-suit pressure: 0 mmHg

	Cardiac Output														
Subject	O2	MIG	TD	HR Start	HR Mid	HR End	Part Start	Part Mid	Part End	Ppa Start	Ppa Mid	Ppa End	CVP Start	CVP Mid	CVP End
	l/m	l/m	l/m												
RT		5.7		61	60	66	83.3	82.7	84.8	•	•	•	-0.9	-0.4	-0.2
KK				•	•	•	•	•	•	•	•	•	•	•	•
FC		0.8	5.9	65	74	70	96.5	99	97	8.9	9.1	8.2	3.5	3.3	4.9
VW		8.9	7.7	75	74	83	100	108.4	92	9	•	9.8	0.4	-3.2	-0.1
WS		5.4	5.3	69	67	61	96.4	98.5	98.1	2.8	3.7	•	0.9	2.4	2.4
TH		6.1	6.3	74	80	81	87.7	86.4	83.2	5.6	•	8.1	0.4	-0.2	1.2
JL		6.8	6.1	89	81	82	90.9	87.8	92.7	7.8	8.9	10.6	5.5	4.9	9.7
TLH		6.2	6.3	90	89	86	93.9	94.6	94.1	7.9	12.3	8.1	-0.7	-0.6	-0.5
SA		8.9	7.5	72	66	71	98.7	99	98.1	9.1	8.5	8.5	8.1	4.9	9.9
TP				•	•	•	•	•	•	•	•	•	•	•	•
MEAN		6.1	6.4	74.38	73.88	75	93.43	94.55	92.5	7.3	8.5	8.88	2.15	1.39	3.41
STD DEV		2.5	0.9	10.42	9.40	9.17	5.75	8.45	5.75	2.33	3.08	1.06	3.24	2.93	4.32

O2 Fick, calculated using the Fick principle from oxygen consumption and the a-v oxygen content difference; MIG Fick, calculated using the Fick principle from the four least soluble inert gases; TD, determined by thermodilution.

Cardiac Output, Heart Rate, CVP, Mean Arterial and PA Pressures

24,900 ft
Mean PB: 283 mmHg
Breathing gas: 100% oxygen
Mask Pressure: 60 mmHg
Counterpressure: 60 mmHg
G-suit pressure: 60 mmHg

Subject	Cardiac Output O2	Cardiac Output MIG	Cardiac Output TD	HR Start	HR Mid	HR End	Part Start	Part Mid	Part End	Ppa Start	Ppa Mid	Ppa End	CVP Start	CVP Mid	CVP End
	l/m	l/m	l/m												
RT		1.5		92	105	108	116	117.6	118.1	48	51.7	46.1	41.2	45.5	40.7
KK				•	•	•	•	•	•	•	•	•	•	•	•
FC		3.0	3.7	124	106	79	138.6	117.6	91.9	63.3	•	59.1	55.4	52.5	•
VW				•	•	•	•	•	•	•	•	•	•	•	•
WS			5.2	126	140	136	102	106.1	85.4	57.7	•	60.9	50.8	48.5	•
TH		4.4	6.3	143	160	170	109.4	112.5	115	55.9	•	65.1	47.1	42.7	38.4
JL		3.2	1.8	120	129	87	147.1	135.4	77.9	60.1	•	61.7	•	60.9	•
TLH		7.3	6.8	128	140	162	142.8	146.1	120.7	58.5	59.5	57.7	46.7	37.5	44.5
SA		5.2	8.8	106	127	157	126.1	137.2	120.4	55.2	59	50.1	48.8	51.8	46.6
TP		4.3		114	148	153	131.4	133.4	117.2	57.3	50.3	49.5	49.1	48.4	44.9
MEAN		4.1	5.4	119.125	131.9	131.5	126.68	125.738	105.825	57	55.125	56.275	48.44	48.475	43.02
STD DEV		1.8	2.5	15.38	19.3	35.52	16.32	14.10	17.68	4.43	4.80	6.83	4.32	7.01	3.36

O2 Fick, calculated using the Fick principle from oxygen consumption and the a-v oxygen content difference; MIG Fick, calculated using the Fick principle from the four least soluble inert gases; TD, determined by thermodilution.

CONSENT FOR RESEARCH - PART II

Name:

Pulmonary Responses to Positive Pressure Breathing

History #

Protocol Number: 1204-93-9

We are asking you to take part in a research study in the Department of Anesthesiology at Duke University Medical Center which can involve exposure to reduced atmospheric pressures equal to those encountered at altitudes of 25,000 feet.

The purpose of this study is to measure the effect of breathing at increased pressure on heart and lung function. Air Force Pilots breathe oxygen from a tank connected via a breathing tube to a tight fitting mask which fits around the nose and mouth. At high altitude the pilot can lose consciousness because of insufficient oxygen in the blood due to the low pressure at altitude. This is counteracted by increasing the pressure in the oxygen breathing mask. This can have adverse effects such as reducing the amount of blood that the heart pumps (cardiac output) and increasing the required breathing effort. In addition the increased pressure could rupture the lung, causing air to enter the space around the lung or the heart and blood vessels with possible collapse of the lung or interference with the heart's pumping efficiency. The risks of these complications are reduced in pilots by providing a pressure vest and a device which compresses the legs and abdomen whenever the breathing pressure is increased. However, the optimum balance between breathing pressure, and chest/leg compression is unknown. This study will determine effects of these factors on breathing, efficiency with which oxygen enters the blood (and carbon dioxide is removed from the blood) and how blood is circulated around the body.

In order to perform the study we will need to insert three plastic catheters. One catheter will be advanced from a peripheral vein through your heart into your pulmonary artery through which blood is pumped to the lung from the heart. An additional catheter will be inserted into an artery into your wrist. A third catheter will be inserted into a small peripheral vein and will be advanced up the arm until the tip just enters the chest cavity. It will be used to infuse a solution of trace amounts of inert (metabolically inactive) gases. Placement of these catheters (tubes) will be performed after injection of local anesthetic and therefore should not be associated with any major discomfort. Risks of placement of these tubes include infection, and allergic reaction to the local anesthetic. Placement of the pulmonary artery catheter may be associated with the tying of the catheter in a knot. If the catheter ties itself into a knot during placement, or damages a heart valve, heart surgery might be required. This risk will be minimized by watching the advancement of the catheter on an x-ray image intensifier. Abnormal heart beats may occur as the tip passes through the heart; these usually last for only a few seconds. However, rupture of the pulmonary artery, bleeding and death could result. The risks of the long peripheral catheter include infection, allergic reaction to the local anesthetic, blood vessel rupture and possible blood clot formation. These risks will be minimized by verification of placement with x-ray image intensifier at the time of insertion of the pulmonary artery catheter and by a continuous infusion of intravenous fluid throughout the study. The risks of the long peripheral catheter are less than those associated with pulmonary artery catheter placement. Arterial catheter insertion can cause occlusion of the blood supply which could lead to loss of your thumb or hand. In order to minimize the risk of this complication we will first perform a test (Allen's test) to determine whether your hand has an additional blood supply (ulnar artery). None of these major complications have been seen in this laboratory. Discomfort can occur after the catheters are removed.

_____

Subject Initials

CONSENT FOR RESEARCH - PART II Name:

Pulmonary Responses to Positive Pressure Breathing History #

Protocol Number: 1204-93-9

During the experimental sessions you will breathe air or oxygen from a mask that is applied tightly to your face. All experimental sessions will be while seated at rest. Each of 10 measurement sessions will last about 10 minutes and will consist of different breathing pressures with or without inflation of the pressure vest and leg compression device total time will be approximately 1 1/2 hours. Studies will occur at sea level and simulated altitude (decreased chamber pressure). While at simulated altitude you will be breathing gas which has increased amounts of oxygen such that blood oxygen will always be at safe levels. Samples of blood (total of 250 ml, or about 1/2 pint) will be obtained from the arterial and pulmonary artery catheters for analysis of the six gases. Prior to the study we will measure the hemoglobin concentration in your blood to be sure that your body will tolerate this amount of blood loss. These measurements will allow a computer reconstruction of the pattern of gas exchange within your lung. The gases used are not toxic in the amounts given, and many have been used in much higher amounts to induce general anesthesia. A training session lasting 1 - 2 hours will be necessary to familiarize yourself with the equipment and procedures, and to ensure that you can perform the tests without discomfort. Total time for the procedures on the actual day of the experiment will be about 5 hours.

The risks of this study include the risks of pulmonary artery insertion (described above) and of altitude exposure (described in Part I of the consent form). The risks of high pressure breathing include entry of air into the space around the lung (collapsed lung) and heart or the blood. While the risk is believed to be low, these complications could result in the necessity of placing a tube in your chest, recompression therapy to pressures greater that atmospheric, or even death.

You may not directly benefit from the results of this study except by learning of your heart and lung function while breathing at increased pressures. However, the overall results of this study may benefit others by estimating the degree to which the respiratory system is impaired at altitude or by breathing gases at increased pressure.

You will be compensated $50.00 for completing the training sessions and an additional $300 for the final study.

It is very important that you read and understand several general principles that apply to all who take part in these studies.

List of General Principles

a) Taking part in this study is entirely voluntary.
b) Personal benefit may not result from taking part in this study, but knowledge may be gained that will benefit others.
c) You may refuse to participate or may withdraw from the study at any time.
d) There will be no charge to you for the research procedures.
e) When results of a study such as this are reported on medical journals or at meetings the identification of those taking part is withheld. Medical records are maintained according to hospital requirements.

_____
Subject Initials

CONSENT FOR RESEARCH - PART II Name:

Pulmonary Responses to Positive Pressure Breathing History #

Protocol Number: 1204-93-9

f) Should you have any questions with regard to this research, you are urged to contact Richard Moon, M.D. at 681-5805.
g) Any significant new findings developed during the course of this research, which may bear upon your willingness to continue participation in the research, will be provided to you.
h) Research Related Injuries: Immediate necessary care is available if an individual is injured because of participation in a research project. However, there is no provision for free medical care or for monetary compensation for such injury. Further information concerning this and the rights of subjects in research can be obtained from the Hospital Risk Management Office, (919) 684-3277.
i) The confidentiality of this study's records identifying you will be maintained within Duke University Medical Center. Your identity will remain confidential if material from the record is used for publication or for educational purposes. However, you should be aware that there is a possibility that the Food and Drug Administration and/or the sponsoring company or agency may inspect the records.

The National Committee on Radiation Protection has set permissible "occupational radiation exposure limits". These limits are defined as "the dose of radiation that, in the light of present knowledge, is not expected to cause appreciable bodily injury to a person at any time during his lifetime." The risk of this amount of occupational exposure for any scientist, radiologist or technologist who is exposed to radiation nearly every day is considered to be very small. At the levels set in 1957 there is thus far no indication of harmful effects to the worker or his offspring. The exposure in this study will amount to 30% of the maximal permissible occupational radiation exposure allowed over a one-year period. The radiation dose we have discussed is what you will receive from this study only and does not include any exposure you may have received or will receive from other tests (for example, the radiation received during your catheterization).

For women of childbearing potential - I understand that since this research may have an adverse reaction on an unborn child and should therefore not be done during pregnancy, it is necessary that a pregnancy test (using 2 teaspoonsful of blood drawn from a vein by a needle stick) be done first. To my knowledge, I am not pregnant at this time. If sexually active, I will take contraceptive measures for the duration of the research.

I have read this Informed Consent, both Parts I and II and have been given the opportunity to discuss this experiment and to ask questions. I have observed the procedures or watched a video of insertion of the pulmonary artery catheter into a vein and its advancement into the pulmonary artery. I have been informed that I may contact Dr. Bryant Stolp at 681-6069 or Dr. Richard Moon at 681-5085 to answer any questions that I may have during this investigation and that I may contact the Office of Risk Management (684-3277) for any question concerning my rights as a research subject. I agree to participate as a subject with the understanding that I may withdraw at any time.

_____

Signature Date

_____

Witness Date

INFORMED CONSENT FORM - PART I

PATIENT RESEARCH

Name:

History #:

Protocol Number: 1204-93-9

The chambers at the F.G. Hall Laboratory can be used to simulate various depths beneath the seas by pumping air into the chambers and thus increasing atmospheric pressure. They can also be used to simulate various heights above the earth by sucking air out of the chambers and thus decreasing atmospheric pressure. Exposure to such changed atmospheric pressures will involve changes in pressure both inside and outside the body. The potential hazards of such exposures may be outlined as follows:

1. Hazards associated with compression or increasing the air pressure inside the chambers (simulation of depths beneath the sea or rapid return to the surface from simulated altitude).

   With compression there is occasional difficulty getting the air pressure in the ears, sinuses, teeth, lungs and intestines to equal the increasing pressure outside the body. Such problems may cause pain and the production of fluid in these spaces. Hearing loss, inflammation of the ear and sinusitis may occur. Usually, these problems are temporary and clear in a few days. Very rarely permanent problems occur. However, if any discomfort is felt during compression, the personnel in the laboratory should be immediately notified so that corrective measures can be taken. Occasionally individuals have air filled cysts in their lungs. If such a person is exposed to increased pressure, the cyst could possibly rupture and cause the lung to collapse, requiring medical and/or surgical treatment such as inserting a tube through the skin into the chest to re-expand the collapsed lung. This complication is rare and, thus far has not occurred in this laboratory in greater than 20 years of experience involving thousands of patient exposures.

2. Risks associated with decreases in air pressure or decompression from simulated depths beneath the sea:

   With decrease in air pressure such as is encountere during decompression from simulated depths, or exposure to simulated altitudes, symptoms such as joint pain can occur and are termed decompression sickness. The cause is thought to be the formation of gas bubbles in the body. These bubbles can cause damage to the brain, spinal cord, death and disability. In this laboratory, the depth as well as the rate of changes in pressure are carefully controlled, and only mild and transient forms of decompression sickness have been seen here, and these occur in less than 1% of dives.

   Early symptoms of bubbles may be pain in the joints, skin rash or, if an individual has had migraines in the past, a migraine headache. If these symptoms occur, either during the test or (and this is important) at any time after the test, the Hall Laboratory personnel should be notified immediately by calling (919) 684-8111 and asking for the

Initials of Patient _____

PATIENT CONSENT FORM - PART I

PATIENT RESEARCH

Protocol Number: 1204-93-9

Name:

History #:

hyperbaric physician on call, for many, but not all, cases of decompression sickness can be cured by prompt recompression.

3. Other hazards associated with exposures to increased atmospheric pressures (simulated depths beneath the sea):

   Exposure to higher than normal oxygen concentrations can cause generalized shaking and even seizures. If a potentially hazardous exposure to an increased amount of oxygen in part of the treatment, the details and risks are thoroughly reviewed beforehand with the subject and are contained in Part II.

   An additional potential hazard associated with exposure to increased atmospheric pressure is destruction of certain parts of long bones. Experts generally agree that this problem is exceedingly rare with exposures to simulated depths of less than 100 feet and/or for exposure times not exceeding three to four hours.

4. Risks associated with exposure to simulated altitudes (sucking air out of the chambers):

   Individuals exposed to simulated altitudes, decreased atmospheric pressures, can become unconscious and seriously harmed if the amount of oxygen available for breathing becomes too low. If a test exposure to a less than normal amount of oxygen is part of the treatment design, the physician reviews thoroughly beforehand with the subject and details and risks of the experiment. The details and risks are contained in Part II. If an individual during an exposure to simulated altitude feels lightheaded or notices any discomfort or unusual sensations, he should notify the chamber personnel immediately. Also decompression sickness as noted above can occur with altitude exposures. This complication is unusual. If an individual develops signs or symptoms of low oxygen or decompression sickness during altitude exposure, the chamber might have to be recompressed or returned to the surface rapidly. This rapid increase in chamber pressure would expose individuals to increased risks of equalizing air pressure to the ears, sinuses, teeth, intestines or lungs with possible injury to these structures as as noted above in the discussion of hazards of compression or increase in the air pressure inside the chambers. These complications are unusual.

5. Risks associated with equipment failure:

   If there is mechanical or electrical failure of part of the pressure tank or of equipment which keeps it operating safely, the exposed humans could be seriously injured or even killed. If a fire occurs within the pressure tank, all exposed humans could be burned or asphyxiated. In over twenty years of operation, there have not

Initials of Patient _____

INFORMED CONSENT FORM - PART I

PATIENT RESEARCH

Protocol Number: 1204-93-9

Name:

History #:

been any instances of structural failure or fire in the Duke chambers. Moreover, all new equipment is subjected to evaluation and testing before its use is permitted in the chamber. A regular preventive maintenance program is utilized for all systems. Nonetheless, the possibility of equipment failure, however remote, cannot be completely eliminated.

6. General risks:

   It is important that individuals about to undergo tests involving the changing of atmospheric pressures understand that many of these tests have never been performed under such conditions before and there may be risks which are unknown. If all was known about what happened or what might happen, there would be no reason to do the tests. Physicians have been instructed to answer any questions concerning risks and safety measures. Individuals about to undergo such tests should also understand that the test should not be done if their consent has been effected by a promise of a large sum of money or by other pressures to participate.

7. Provision of care:

   Immediate necessary care is available if an individual is injured because of participation in this treatment. However, there is no provision for free medical care or for monetary compensation for such injury. Further information can be obtained from the Hospital Risk Management Office at 684-3277.

8. Photography:

   I hereby give permission to Duke University Hospital to make any photographs for diagnostic purposes and/or to enhance the medical record. I further authorize the use of such photographs for teaching purposes or to illustrate scientific papers or lectures without inspection or approval on my part of the finished product or the specific use to which it may be applied. My identiy will be protected.

9. Pregnancy statement:

   There is evidence to support that the frequency of birth defects is significantly greater among children from pregnancies during which women have been exposed to increased pressures asfor example in diving.

   It is therefore necessary that a pregnancy test be done first on women of childbearing potential. To my knowledge I am not pregnant at the present time. Further, if sexually active, I will take contraceptive precautions for the duration of this treatment.

Initials of Patient _____

PATIENT CONSENT FORM - PART I

PATIENT RESEARCH

Name:

History #:

Protocol Number: 1204-93-9

10. Statement by subject:

I have read Parts I and II of this Informed Consent and have been given the opportunity to discuss this treatment and to ask questions. I have been informed that I may contact _____ (Physician) at _____ (telephone #) to answer any questions I may have during this treatment. I agree to participate as a patient with the understanding that I may withdraw at any time except for the necessity of staying in the chamber for the time required for decompression.

_____ Signature

_____ Date

_____ Witness